Fermilab
FY2002 Self-assessment
Process Assessment Report
For
Technical Division

26-Apr-2002

Division/Section performing assessment

Personnel from Fermilab, LBNL, FSU and BNL

Name of organization that owns assessed process

Technical Division

Organization Strategy

Part of the mission of Technical Division is to conduct research in superconducting materials and magnets. The High Field Magnet (HFM) program seeks to develop the technology to fabricate magnets with the highest field strengths possible.

Names of Personnel on Assessment team

John Peoples, Fermilab
Jim Strait, Fermilab
Steve Gourley, LBNL
Steve Van Sciver, FSU
Peter Wanderer, BNL

Name of process assessed

High Field Magnet R&D program.

Brief description of process to be assessed

The purpose of the High Field Magnet R&D program is to develop the technology to fabricate magnets with the highest field strengths possible. These magnets could be used in future HEP facilities, and other unknown industry-specific applications.

Are metrics associated with this process? If so, what are they?

The High-Field Magnet program is part of the contractual metric in Performance Area 1:

Critical Outcomes, I. Science Programs. The DoE Office of Science will evaluate the quality and effectiveness of the program.

What are the names of the procedures associated with this process?

There are no specific procedures associated with this process. However, the guiding principles of the R&D program are a result of the goals of the overall High-Energy Physics program, and the recent report published by the HEPAP (Long-Range Planning for U.S. High-Energy Physics).

Are these procedures being followed? Are they current?

The assessment showed that the high-field program is working within the framework defined in the HEPAP report.

Describe the methodology used to assess this process.

This assessment was conducting by holding a review of the overall superconducting magnet program at Fermilab, which resides in the Technical Division. The committee was charged with reviewing the status, accomplishments and direction of the program. Much of the review was focused on the high-field magnet program.

The project leaders made presentations to the review committee, and discussions followed the presentations. At the end of the review, the committee published a report summarizing their findings (see attached).

Results of the assessment:

The committee concluded that the existing process controls are sufficient for conducting the research, resulting in a rating of **good**. No major deficiencies were identified. There are some areas which could (and should be improved), which will be reviewed in more detail below (see attached report for details).

The committee commended the HFM research team for their 47 contributions made to conference proceedings and papers in the 2.5 years the project has been running.

This project has not been assessed before, and so there is no prior comparison to be made. There was a recent DoE review (May 2002), but the summary report is not available.

Identified opportunities for improvement

Overall the process is working effectively. The committee did suggest a few ideas for making improvements:

1. The HFM research team should work more closely with similar teams at other institutions, e.g. LBNL and BNL.
2. Capitalize on the similarities between the common coil/racetrack and cos(θ) R&D paths, and expand the R&D capabilities of the simpler racetrack program as a means of studying potential improvements that could be incorporated into the cos(θ) program.

3. Integrate the overall HFM effort with the national superconductor program managed by the DoE Division of High Energy Physics.
4. The committee recommended that Fermilab conduct informal design reviews of each of its new model magnets before fabrication has started.
5. The committee recommended that the three laboratories and other players engaged n superconducting magnet R&D hold periodic mini-workshops on magnet R&D topics.
6. The committee recommended that the Head of the Technical Division form an external advisory committee to help monitor and evaluate the progress on superconducting magnet technology made by Fermilab and other major players in this area.
7. The committee recommended that the Fermilab Nb_3Sn development program be reviewed to ensure that the processing changes being explored are consistent with the processing changes being made by industry to meet the goals of the DoE national Nb_3Sn program.

Schedule for implementation of improvements

The HFM team has not put a schedule together for the implementation of the recommendations from the review. The HFM project will instead incorporate the recommendations as they are able to.

Status of improvements from previous assessment

N/A.

Attachments (supporting data, worksheets, reports, etc.)

The following attachments have been incorporated into this report:

"Committee Report" - This is the report published by the review committee summarizing the entire review (note there are sections in the report which do not apply to the assessment of the HFM program).

"Presentation 1" - Presentation by Sasha Zlobin on 'HFM R&D Program Overview'

"Presentation 2" - Presentation by Vadim Kashikhin on 'HFM Design Considerations'

"Presentation 3" - Presentation by Deepak Chichili on 'Design and Fabrication of Nb_3Sn Cos(θ) Dipole Models'

"Presentation 4" - Presentation by Sasha Zlobin on 'Cos-theta dipole test results'

"Presentation 5" - Presentation by Sasha Zlobin on 'Future Plans for SC Magnet Program'

Report of the Review Committee On the Fermilab Superconducting Magnet Program (FNAL, 25-26 April 2002)

J. Peoples (Chairman), S. Gourlay, J. Strait, S. Van Sciver, and P. Wanderer

Foreword

The Head of the Technical Division, Robert Kephart, appointed the Committee to review the status, accomplishments, and direction of the Fermilab Superconducting Magnet Program, which is carried out in the Technical Division. In January of this year the High Energy Physics Advisory Panel recommended to the Department of Energy that it support the construction of a 500 GeV center of mass linear collider as its next major facility for high-energy physics. It also recommended that R&D for a Very High Energy Collider, which could succeed the LHC at the energy frontier, be continued, although first priority for accelerator R&D would be given to the linear collider. The Committee was informed at the review that the level of support for the Superconducting Magnet Program was expected to remain about the same in the near future as it had in the recent past. It was against this background that the Committee was asked to carry out its review.

The Committee met at Fermilab on 25 and 26 April 2002. During the first day and a half the Committee received presentations from the Technical Division Staff that covered the Tevatron Magnet Program, the LHC IR Project, the magnet R&D efforts for VLHC designs, and the facilities that are used to support the entire superconducting magnet program. The staff also gave the Committee a tour of these facilities during the review. The Committee held a teleconference on 17 May 2002 and reviewed the draft report.

The Committee's report begins with an introduction that briefly describes the nearly thirty-year history of the work on superconducting magnets at Fermilab, thereby providing an historical context for this report. This is followed by findings, which are drawn from the presentations on the three major subprograms in the current program: the Tevatron Magnet Program, the LHC IR Project, including the participation in the integration of the quads into the LHC Collider, and the Nb_3Sn magnet R&D program. Since some of the presentations described the facilities for magnet fabrication, magnet testing, and the evaluation of materials that are used in the construction of superconducting magnets one sub-section of the Committee's findings is dedicated to those facilities. Conclusions and recommendations are presented in the final two sections of the report, and it is in those sections that the Committee responds to the specific elements of the charge. The charge, the membership of the Committee, and the list of review participants are contained in Appendix 1, and the review agenda is presented in Appendix 2.

The Committee thanks the Technical Division Staff for the carefully prepared and presented presentations and for the open atmosphere of the review that allowed the Committee to respond to the charge. The Committee further thanks the staff for the excellent administrative support during the meeting and after the meeting.

John Peoples, chair
Stephen Gourlay
James Strait
Steven VanSciver
Peter Wanderer

1 Introduction

Fermilab has been engaged in the development and fabrication of superconducting magnets for accelerators for nearly thirty years. The development of a dipole magnet for the Energy Doubler began soon after the Main Ring delivered 200 GeV protons to fixed target experiments in 1973. When the work began, every aspect of accelerator systems had to be invented for what would become the world's highest energy accelerator. Even the names of Fermilab and the Tevatron were part of the future. During the next ten years Fermilab developed all of the technologies for a superconducting proton synchrotron, including superconducting wire and cable, liquid helium cooling systems, quench protection systems, and the manufacturing techniques that produced accelerator-quality magnets. In many instances Fermilab extended a technique that had worked on a small scale in the laboratory to the much larger scale that was required for the Tevatron.

The first period of development drew to a close when the Tevatron delivered beam to fixed target experiments in 1983. Over the next eight years (1984-1992) Fermilab put most of its development efforts into the transformation of the Tevatron into a collider. The superconducting magnet development was focused primarily on the fabrication of high gradient quadrupoles for the Tevatron low beta interaction regions (IR's). The first high gradient quadrupoles for the CDF IR (1983-1986) were practical magnets that used the best available conductor that could be produced in industry in 1983. There was not time to develop better superconductor since so many accelerator systems problems had to be solved to make even a primitive low beta insertion work in the Tevatron. The insertion consisted of just eight magnets, and the value of ß* was a little more than 1 meter. Fermilab continued to work with the wire and cable industry to produce better wire and cable since higher gradient quadrupoles would be needed to produce matched low beta insertions and higher luminosity. After the D0 detector was approved in 1984, the effort was focused on building quadrupoles for the two matched insertions for CDF and D0 IR's. Since the goal of the program was to produce a ß* of less than 0.5 m at the two experiments, a total of forty magnets had to be built. The main triplets for these insertions required a gradient of 140 T/m to meet the ß* requirement, much stronger than had been produced in existing superconducting quadrupoles. The laboratory-industry effort produced cable that supported these designs, and when the low beta quads were completed in 1990 they were the highest gradient quadrupoles in existence. The fully-matched insertions were far more complex than the first CDF low beta insertion since each insertion required twenty magnets, consisting of ten different types of magnets with separate power leads. As before, the focus was on building practical, high-quality magnets. The insertions were a success and an important contributor to the luminosity that enabled the discovery of the top quark in 1995. These insertions are still in use. During the next several years Fermilab also built low beta quadrupoles for the SLD IR at the Stanford Linear Collider.

Along with BNL and LBNL, Fermilab was a member of the SSC Central Design Group collaboration that developed the 7 Tesla dipole for the SSC. When the work began in 1984, Fermilab was responsible for the design, development, and fabrication of the cryostats for the SSC-CDG dipoles and the integration of the cold mass and cryostat to produce a testable magnet. Fermilab was also responsible for testing the completed magnets in the Fermilab Magnet Test Facility. A second dipole cold mass production line was opened at Fermilab in late 1987 when the CDG expanded Fermilab's responsibilities to include the fabrication of SSC-CDG dipole cold masses. During the next five years, Fermilab made major improvements to the manufacturing techniques for the SSC cold masses and cryostats. Fermilab and BNL produced the 17 m dipoles for the successful SSC string test in 1992. After the string test dipoles were completed, the funding for superconducting magnet development dried up at Fermilab and the Fermilab magnet program was suspended.

In the wake of the termination of the SSC project in late 1993, HEPAP recommended to the Department of Energy (DOE) that the U.S. participate in the LHC scientific program. Subsequently the DOE, the NSF, and Congress agreed to fund the U.S. participation in the LHC. During 1994 and 1995, Fermilab led the formation of the three-laboratory collaboration among BNL, Fermilab, and LBNL that proposed the U.S. contribution to the LHC Collider. Fermilab was designated as the host laboratory for the U.S. contribution and was given responsibility for overall management of the U.S. contribution. It was responsible for the development of the low beta quadrupoles for the four IR's. This included the fabrication and testing of model magnets and full-length prototypes for LHC low beta quadrupoles. After successfully completing the prototype phase, Fermilab was responsible for the design, fabrication, and testing of accelerator-ready low beta quadrupoles. This phase is still underway and will be completed in 2004 when all of the quadrupoles will have been delivered to CERN. The fabrication of the 205 T/m high gradient quadrupoles for the LHC low beta insertions is a natural continuation of the line of development of high gradient quadrupoles that Fermilab began nearly twenty years ago.

Beginning in 1995, Fermilab began to pursue several designs for a VLHC, a 100 TeV proton-proton collider that could be the successor to the LHC. One design was based on a 2 Tesla superferric dipole and the other on a 12 Tesla, Nb_3Sn dipole. By 1998, a modest magnet R&D program was underway for each approach. These separate programs continued until now. The Laboratory informed the Committee during the review that it has elected to stop the development of a superferric magnet system and concentrate on the 12-Tesla magnet. In each case, the emphasis was placed on developing an accelerator magnet that was part of a practical accelerator system. These R&D magnets were used to explore the parameter space for a possible VLHC.

2 Findings

2.1 Tevatron Magnet Program

The Tevatron will continue to be the highest energy collider until the start of the LHC physics program, which is now scheduled to begin in the second half of 2007. The opportunity for exploiting the Tevatron for another decade needs to be tempered with the realization that it has been in operation since 1983. Many of its subsystems were still under development when commissioning was completed, and they have needed rebuilding and repair based on the experience that was gained in the first few years of operation. This should not be surprising because it was the first superconducting proton synchrotron, and the need to repair and rebuild continues to this day. The magnets that are removed from service are repaired or rebuilt, tested, and their field properties carefully measured, recorded, and thoroughly documented. The Technical Division is responsible for maintaining an accelerator-ready set of magnet spares for the Tevatron, and it carries out these activities in order to fulfill these responsibilities. All of the major departments in the Technical Division take part in these activities.

The Technical Division must maintain thirty-five different types of superconducting magnets in the spares pool. These consist of two types of main dipoles, eight types of arc quadrupoles, ten types of low beta insertion quadrupoles, and fifteen types of correction magnet systems (spool pieces). The Tevatron contains more than four hundred of each type of main dipole, and there are 189 arc quadrupoles installed in the Tevatron.

Typically five to ten main dipole magnets have to be replaced every year. In some cases, more than one magnet has to be replaced when a single magnet fails in order to provide the proper lattice properties for the cell in which the magnet fails. Arc quadrupole magnets have to be replaced less often, partly because there are only one fourth as many of these magnets as there are dipoles. Spools fail in greater number since there are so many and because the complex connections for helium and vacuum are in the spools. Most magnets have to be taken out of service because of leaks in the cryogenic or vacuum connections or failures of the power leads. About once a year a main dipole suffers a serious failure and has to be scrapped. Only one arc quadrupole has had to be scrapped in the past decade.

There are at least five Tevatron qualified spares for each of the two types of main dipoles, and there are nine spares for the most common type of arc quadrupole. While there is at least one accelerator-ready spare for each of the other types of magnet, the number of spare spools is of some concern. Nevertheless, the Beams Division believes that this inventory is adequate for the typical types of failures that have been encountered over the past twenty years. The Committee concurs in that assessment, but notes that the repair program must be sustained in order to keep the inventory from dropping to marginal. The Committee notes that it was stated in the presentation of the Tevatron magnet program that the Laboratory has begun a vulnerability assessment of the Tevatron spares pool. This work needs to be completed before the knowledge is lost through retirements.

The maintenance of the Tevatron spares pool is a major effort that is very effectively carried out by the Technical Division. The Technical Division is also responsible for maintaining the magnet spares pool for all of the conventional accelerators and beam lines in the Fermilab accelerator complex. The organization of the Technical Division is shown in Figure 1.

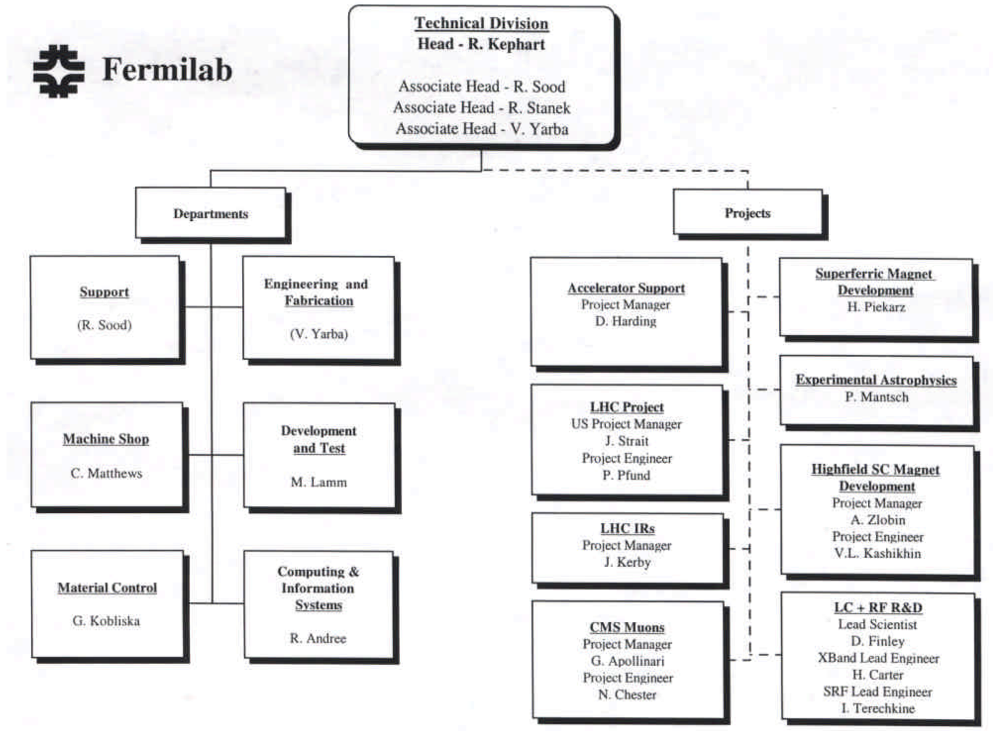

Figure 1 Organization of the Fermilab Technical Division.

The repair and rebuilding work is carried out by the Engineering and Fabrication Department, which also builds the LHC low beta quadrupoles and the high field Nb_3Sn R&D magnets. It also repairs the conventional magnets for all of the accelerators and beam lines in the Fermilab accelerator complex and builds the one-of-a-kind conventional magnets as well. The Material Control Department is responsible for obtaining, inspecting, and storing sufficient qualified parts for the repair and upgrade of accelerator magnets for all of the accelerators as well as the fabrication of new magnets. The Development and Test Department is responsible for testing and measuring all accelerator and beam line magnets. In particular it is responsible for testing and measuring the LHC low beta quadrupoles and the high field Nb_3Sn model magnets. It is also responsible for the conceptual designs for the Nb_3Sn model magnets and provides the direction for the R&D program.

The Technical Division has extensive facilities for designing, fabricating, and testing superconducting magnets. It also has facilities for testing materials that are used in superconducting magnets, including superconducting wire and cable. The primary purpose for these facilities is to support the Tevatron. The maintenance of drawings and the documentation of manufacturing processes, inspections, tests, and measurements is a major activity for all of these departments.

In recent years these departments have been engaged in a program to upgrade the spools. Fourteen spools have been repaired and equipped with recoolers. They have reduced the single-phase He temperature by improving the heat transfer between the two-phase He and the single-phase He. Except for spares, all of the spools equipped with recoolers have been installed in the Tevatron at spots where there is a weak magnet. This should make it possible for such magnets to reach a higher operating current without quenching. The Tevatron has reached 0.98 TeV through improvements such as this. The impact on the Tevatron energy due to the recoolers was not known at the time of the presentations. A program to replace the power leads in the power spools with high temperature superconductor leads has been initiated, and three spools have been rebuilt with these leads. One of these new power spools has been installed in the Tevatron. The intent is to build and install ten power spools and thus reduce the cryogenic load created by lead heating. The feed throughs for the corrector magnet leads for the spools have been a reliability problem for a long time because they develop vacuum leaks when ice balls form. A connector has been developed that is much less susceptible to this problem, and ten of twenty-four houses have been installed with the retrofitted spools. A large work force is needed to make the replacements during the short shutdowns of the Tevatron. The Technical Division is able to provide these resources by diverting their skilled technicians from R&D magnet fabrication, magnet repair, and magnet production during the shutdowns.

The Committee found that the Laboratory had not made a quantitative assessment of the value of these improvements. The Committee urges the Laboratory to do this, since it is necessary to evaluate the effectiveness of the improvements.

2.2 LHC IR Project

The construction of the LHC Interaction Regions involves the three-laboratory collaboration of Fermilab, BNL, and LBNL, as well as CERN and KEK. The LHC IR project consists of the following tasks:

1. Design, build, test, and deliver the inner triplet cold masses. This consists of 16 quadrupole magnets plus two spares built by Fermilab, plus an additional 16 plus two spares contributed by KEK.
2. Fermilab designs, builds, and fabricates the cryostats for all of the IR quadrupole magnet assemblies and integrates Fermilab cold masses, KEK cold masses, and CERN-supplied components, such as correctors, into the final magnet assemblies. These assemblies will be ready for installation.
3. BNL designs and builds the beam separation/recombination dipoles that bring the two beams into collision.
4. LBNL designs and builds the cryogenic feedboxes for the inner triplet quadrupoles and beam separation dipoles, and special absorbers to protect the superconducting magnets from the collision debris.

The LHC IR quadrupole program, with NbTi superconductor, is proceeding very well. It has been underway since 1995, when it was started with Laboratory funds that continued until 2000. In 1996, project funds from the US LHC program started, and since 2001 the program has been completely supported by the US LHC project. The design, development, and prototype stages were successfully completed and production is underway. The quench performance of the full-length prototype has met and exceeded the design requirements of 205 T/m at 1.9 K. The model magnets (HGQ05-09) trained to 230 T/m or above at 1.9 K during the first thermal cycle and typically exceeded 220 T/m in the following thermal cycles. The field quality of the final magnets will meet requirements. The LHC IR cryogenics system, on which these low beta quads are based, was successfully tested in CERN in 2001. The integration of components with rather different dimensions such as the KEK cold mass and the Fermilab cold mass has been successful. Production is scheduled to be completed in 2004.

Fermilab is on track to meet the technical, cost, and schedule goals of the LHC IR Project. It is a good example of Fermilab's strength in producing state-of-the-art magnets for accelerators. Fermilab has a long history of successful small-scale production of superconducting devices, and their unique capabilities have been successfully demonstrated in this project. The LHC IR Project is also an excellent example of a successful multi-lab collaboration, and the collaboration should be extended to the Nb_3Sn model magnet program.

After 5 to 7 years of operation at the design luminosity, it is anticipated that CERN will need to replace the LHC IR quadrupoles because of radiation damage. This is also seen as an opportunity to significantly improve the luminosity. The current design of the LHC machine is already a very high performance accelerator, pushing the limits of NbTi superconductor. The performance and lifetime requirements will require the use of high-performance superconducting materials in the second generation quadrupoles. All materials suitable for this purpose have brittle properties and are much more difficult to incorporate into magnet designs than NbTi. Of the candidate materials, the greatest experience is with Nb_3Sn. This technology, as applied to accelerator-type magnets, has been successfully demonstrated in 1 m models. There is a lot of work to be done, and it will be necessary to start this work as soon as possible in order to meet the time constraint. An aggressive R&D effort will be required to produce magnets with the necessary performance characteristics. This program provides the first opportunity for the application of recently developed Nb_3Sn technology to magnets that will be used in an operating accelerator, and it represents a significant step in the development of Nb_3Sn for future applications .

The Fermilab staff has developed a cost and schedule for the R&D needed for these magnets. The work begins with quadrupoles built using as much of the present quadrupole tooling as possible, for both economy and speed. The schedule is consistent with the LHC schedule. The costs, including manpower, are consistent with the R&D effort needed for the present LHC quadrupoles

In the context of plans for the magnet group as a whole, the lessons learned in the Nb_3Sn high field dipole program will be used in the design of the Nb_3Sn quadrupoles, and the effort of the staff transferred from dipoles to quadrupoles as appropriate. The transition will need careful attention. There was informal discussion that B-TeV may be able to use quadrupoles of the same specifications to take advantage of the LHC Nb_3Sn work. This would clearly be an advantage.

2.3 High Field Nb_3Sn Magnet Program

The principal components of the Nb_3Sn high field magnet program include development of a 12 T cos(θ) dipole, a 12 T common coil dipole, and a high gradient cos(2θ) quadrupole. Significant ancillary programs include work on Nb_3Sn wire and cable and a racetrack coil program. The R&D program draws on a large group of talented and enthusiastic scientists, engineers, and technicians. It also supports the largest number of students of any of the three U.S. programs, and in the last three years will have produced 3 Laurea theses and one PhD dissertation. This is an important aspect of a long-term R&D program. In providing a training ground for magnet physicists, the R&D program allows students to make significant contributions to the current program while gaining experience that will be invaluable to this and future magnet programs.

The Nb_3Sn magnet R&D program was started in 1998, and during its first two years the major efforts were the design of magnets and the acquisition of special equipment. It was not until 2000 that enough resources could be applied to the fabrication of model magnets using Nb_3Sn wire, and since then there has been a steady increase in the staff allocated to this work. Considering that the program has been in existence for only a short time, its goals are quite ambitious. The team has already made several significant contributions to the field while struggling to achieve overall success. For example, the ceramic insulation with non-organic binder is a real advance in coil manufacturing technology. The model magnets have also demonstrated a promising method for the correction of magnetization effects. In addition, these magnets have demonstrated that a stainless steel core in the cable can reduce eddy current effects that have plagued Nb_3Sn magnets in the past. The structural design of the common coil magnet shows good promise. Despite the disappointing quench performance of the first two cos(θ) dipoles, they gave the first real data on the reproducibility of field quality in Nb_3Sn coils. The program appears to be on the threshold of making significant accomplishments. Many paths are being followed, which is a real strength if the various paths are adequately supported and coordinated. However, it is essential that each path have adequate intellectual input to ensure its success.

Fermilab proposes to transform the cos(θ) dipole magnet program into a cos(2θ) quadrupole program for the next generation LHC IR quadrupole. It is clearly important, both for the future LHC IR program and for the Fermilab high field magnet program as a whole, that Fermilab bring the cos(θ) dipole program to a successful conclusion. It is anticipated that this may require several more model magnets to be built and tested. Given limited resources, it is important that the transition from dipoles to quadrupoles be well thought out so that as much as possible that has been learned from the one can be directly applied to the other.

A common coil design, which offers the possibility to use react-and-wind methods, is being developed as an alternative to the traditional cos(θ) dipole design. The particular design being pursued attempts to include all features required of a real accelerator magnet. It utilizes a number of innovative features, including non-flat coils and bridge reinforced collars. This design shows real promise as a candidate for an actual accelerator magnet. Fermilab is preparing to build a first model magnet of this type. The Committee believes that Fermilab should proceed slowly with it, concentrating initially on mastering Nb_3Sn technology through simpler and lower risk tests. It may make sense to begin with a wind-and-react model to reduce the number of new technologies that are attempted in a single model.

The racetrack coil program offers the possibility to quickly test and develop many aspects of Nb_3Sn technology, especially but not only related to the common coil approach to high-field dipoles. It is important that this unique element of the general program be continued and given sufficient priority, as it offers the possibility to learn about and solve magnet technology problems before designs are committed to real magnets, where the stakes are higher. In the context of the inherent challenges in this approach, Fermilab is making good progress. Support for this program should be continued and expanded. There appears to be significant overlap between the common coil/racetrack and $\cos(\theta)$ R&D paths. It would be more efficient to capitalize on these similarities and expand the R&D capabilities of the simpler racetrack program as a means of studying potential improvements that could be incorporated into the $\cos(\theta)$ program.

The work on low-field magnets and racetrack coils are excellent examples of innovative R&D programs where new design options and key performance drivers are broken down and investigated individually. Given the long-term nature of the magnet program and the emphasis on cost reduction, it is recommended that some of these elements be incorporated into the work on high field magnets. Design parameters that are now considered as "given" should be reexamined in the light of possible benefits. Self-imposed design constraints should be challenged at every opportunity.

The Committee found that the Fermilab program has not benefited as much as it could have from the experience and current work of other magnet programs, in particular those at LBNL and BNL. Some of the difficulties that Fermilab has encountered in the Nb_3Sn magnet effort might have been avoided by learning how others have solved similar problems. The modes of communication with other groups cited during the review, principally the presentation of papers to and conversations with other groups at conferences, have not provided adequate information transfer between the different magnet programs. The committee notes that the 47 contributions to conference proceedings and papers is an impressive output for just two and a half years.

The Committee concludes that it is important that priority be given to solving basic technological problems and identifying the fundamental strengths and weaknesses (or even viability) of each design, given the immature nature of Nb_3Sn technology and the long lead times before magnets must be produced for use in a real accelerator. The Committee concluded that it did not appear to be necessary to fully develop the passive correction schemes at this time. Priority should be given to lines of development that have a higher probability of success, at least until the program has an established record of success, in preference to more speculative ideas, such as non-impregnated coils.

2.4 Facilities and Materials

The Fermilab magnet program has put together a superb infrastructure for the production and testing of superconducting magnets. Facilities for materials evaluation and development have been added within the past two years. During the presentations and the tour, the Committee was shown an impressive grouping of facilities dedicated for support of magnet development and production. These facilities, which have benefited significantly from upgrades needed to test the LHC quadrupoles, give Fermilab world-class capability in this area and will be of great value in future magnet programs. The facilities include equipment for development of Nb_3Sn cable (cabling machine, heat treatment, etc.), a high field (up to 17 T), short sample dewar for testing at variable temperatures and including capability to apply transverse loading, a vertical test facility for model coil evaluation, and a horizontal test facility for prototype and production coil evaluation. The latter two systems have capability for reduced temperature operation (T = 1.9 K) and are thus applicable to LHC project work. Several novel test rigs have been developed for use in testing strands under various conditions of stress and strain. Other equipment includes conductor heat treatment furnaces, optical and scanning electron microscopes, coils for measuring the harmonics and quench locations, and a stretched-wire measurement system.

Fermilab has correctly recognized the importance of having an expert on superconductors on staff. The young team of magnet scientists has done a good job of setting up the facilities needed for processing and testing Nb_3Sn strand and cable. Some of the tests are of central importance in magnet design, such as the clever method of testing the stress sensitivity of a wire in a cable. Others are less clear in value, such as the measurement of strain sensitivity, which has been made many times and is not different on the present conductors. Similarly, at least some of the heat treatment experiments are repeating previous (unpromising) work.

3 Conclusions

The Committee reached their conclusions from its findings given in Section 2, and the major conclusions are described in this section. The Committee drew additional conclusions and included them in Section 2 since they were best understood as part of the findings.

The integration of the three major subprograms of the Fermilab magnet program within the Technical Division has been very effective, and it will continue to be the appropriate organization to manage these subprograms. The subprograms are the Tevatron Magnet Program, the LHC Interaction Region project, including the development quadrupoles for the next generation LHC IR’s, and the high field magnet R&D program based on Nb_3Sn technology. The Committee concluded that the size and structure of the organization is well-adapted for the needs of Fermilab and the national superconducting magnet development program. The Technical Division has simultaneously maintained the Tevatron magnet spares pool, refined the manufacturing and testing techniques that it used to build the Tevatron, including substantial upgrades of the facilities that were used to manufacture and test superconducting magnets, and been the engine for the development of improved superconducting magnets that use the NbTi wire and cable technology, since it completed the production and testing of the superconducting magnets for the Tevatron in 1982. The program that led to the development of Tevatron IR quadrupoles is particularly notable. The continuous improvements in the efficiency and luminosity of the Tevatron are very strong pieces of evidence for the success of this approach.

The Committee concluded that the three-laboratory collaboration, consisting of Brookhaven, Fermilab, and Lawrence Berkeley Laboratory, is very effectively producing the U.S. deliverables for the LHC Collider. The evidence that this program is very well managed can be found in the facts that the U.S. LHC Collider project is on schedule and budget and the deliverables will meet the technical requirements. While the Committee did not review the contributions of BNL and LBNL, the committee members know that these contributions are going very well. The Committee did review the Fermilab contributions to this project and concluded that Fermilab will build IR quadrupoles that will meet the technical performance requirements established by CERN, and they will deliver these magnets on schedule and within the budget allocated by DOE. These 205 T/m quadrupoles are an important advance in superconducting magnets based on NbTi wire and cable technology. The Committee congratulates Fermilab for their work.

The Committee concluded that now is the appropriate time to begin the R&D for the next generation of higher gradient IR quadrupoles for the LHC, since CERN must replace the quadrupoles that are now in production after five to seven years of operation at the design luminosity because of the radiation damage that they will suffer during those years. The three-lab collaboration proposes to explore a number of design options since the actual needs for an upgraded LHC IR are not yet known. Within this context, Fermilab has proposed to develop a cos(2θ) quadrupole that uses Nb_3Sn wire. It has the same operating gradient of 205 T/m as the first generation quadrupoles, but a larger aperature of at least 90 mm and a larger temperature margin. The short-sample limit of this magnet is close to 12 T, and so they propose to begin by completing the development of a 12 T cos(θ) dipole. They have selected this development path because they believe that the dipole will allow them to develop the Nb_3Sn cable technology and the manufacturing techniques more rapidly. The Committee concurs with this approach and concluded that the long-term technical goal of building a high gradient cos(2θ) quadrupole based on this technology is the right goal for Fermilab, in collaboration with the other two laboratories. The Committee also concluded that the technical milestones to reach that goal need better definition if the goal is to be reached in time to produce IR quadrupoles for the LHC.

The Committee concluded that the development of Nb_3Sn wire and cable for high field magnets, including the replacement LHC IR quadrupoles, is a challenging and essential objective for the U.S. superconducting magnet program. The Committee concluded that Fermilab has made some valuable contributions in this area and that it could make a stronger contribution if its effort was more closely integrated with the national superconductor program managed by the DOE Division of High Energy Physics..

The Nb_3Sn conductor and cabling characterization work is a generic development activity that should be of interest to a broader range of participants in the field. The level of effort is reasonable considering the importance of the task. Long-term planning proposes an effort increase of approximately 1 MY. Such an increase may be reasonable; however, the Committee was unable to evaluate the future since no detailed work plan was given at the review. It was also not clear how the conductor/cable program is monitored within the context of the Fermilab program or how priorities are established.

Once it has been established that a Nb_3Sn cos(2θ) quadrupole is the most suitable development path for the next generation IR quadrupoles, the Fermilab magnet effort should focus on quadrupoles for the LHC, while continuing to develop a high field dipole. The Committee notes further that if the history of the Tevatron over the past twenty years is a useful guide to the future then quadrupoles of this type are likely to find applications in the post-LHC Tevatron low beta IR's as well as in the LHC.

The Committee concludes that the Technical Division objective to develop a magnet system for a 100 TeV collider, the VLHC, is consistent with the HEPAP twenty-year road map. The Laboratory has elected to set aside the low field, superferric approach to the VLHC, although a great deal has been accomplished in this program with modest resources. The Committee concurs with the Laboratory decision to carefully document its accomplishments so that it may be resumed at some time in the future should the need arise. The Committee notes that the Nb_3Sn technology is not sufficiently developed to allow reliable cost estimates to be made. However, it is important to pursue this technology to determine if its promise can be fulfilled. The Committee's conclusion is reinforced by the fact that Nb_3Sn technology is the only plausible approach for larger aperature IR quadrupoles for the LHC. The Committee agrees with the Laboratory that it must suspend the superferric effort in order to meet its obligations to the Tevatron Magnet Program and the LHC IR project, while keeping the current level of support for the overall program about constant. In light of Fermilab's decision to greatly expand the level of its R&D effort on a 500 GeV class linear collider, there will not be sufficient funds to pursue the development of two magnet systems for the VLHC.

4 Recommendations

The recommendations that flow from the findings and conclusions are described in this section.

The Committee recommends that Fermilab continue to support all three subprograms of the current magnet program at the current level. The Committee recommends further that Fermilab focus its superconducting magnet R&D effort on the development of Nb_3Sn accelerator magnets.

The Committee recommends that Fermilab complete the Tevatron magnet vulnerability assessment promptly, in order to determine whether the spares pool will be adequate during the next ten years.

The Committee recommends that Fermilab commit to be a major participant in the development of the replacement of the high gradient quadrupoles for the LHC IR's. It would be very appropriate for Fermilab to play the same role in the cold mass production and magnet integration and testing that it is currently playing in the LHC IR Project.

The Committee recommends that Fermilab expand its contacts with the other institutions involved in this work:

1. Superconductor. The Committee feels that it would be highly advantageous to coordinate the Nb_3Sn conductor and cable efforts more with ongoing work in industry, other laboratories, and universities. Possible avenues for this increased cooperation might include more frequent workshops, specific reviews of the conductor development activities, and increased use of web-based communications.
2. Magnets. The VLHC effort included regular meetings for progress reports and the exchange of useful details about technological developments of common interest. It would be desirable to set up a similar mechanism for future magnet work, possibly through work on Nb_3Sn upgrade quadrupoles for the LHC.

The Committee recommends that Fermilab conduct informal design reviews of each of its new model magnets before fabrication has started. The Committee further recommends that LBNL or BNL superconducting magnet experts participate in those reviews, since this would strengthen Fermilab's contacts with BNL and LBNL, the other laboratories engaged in the fabrication of R&D model magnets. Similarly LBNL and BNL should also create stronger contacts with the Fermilab magnet program by carrying out similar reviews of their model magnet designs. The Committee recommends that the three laboratories and other players engaged in superconducting magnet R&D hold periodic mini-workshops on magnet R&D topics.

The Committee recommends that the Head of the Technical Division form an external advisory committee to help him monitor and evaluate the progress on superconducting magnet technology made by Fermilab and other major players in this area. The committee specifically recommends that the Fermilab Nb_3Sn development program be reviewed to ensure that the processing changes being explored are consistent with the processing changes being made by industry to meet the goals of the DOE national Nb_3Sn program.

A final observation

The Committee wishes to make a final observation in concluding its report. When the SSC Project was terminated in October 1993, the U.S. superconducting magnet development was concentrated exclusively in the SSC, except for small programs in Berkeley, Brookhaven, and academia that were directly supported by the DOE Division of High Energy Physics. The Department had questioned the value of the Fermilab program, since the SSC was expected to displace the Tevatron as its premier energy frontier facility before the year 2000. From these ashes the Technical Division has restored the Fermilab superconducting magnet program to the point where it can contribute its traditional strength in developing production processes for building and testing superconducting magnet systems for energy frontier accelerators for the national high energy physics program. The LHC experience has demonstrated that Brookhaven, Fermilab, and Lawrence Berkeley Lab can work together in the national interest. The leadership of the Fermilab Technical Division, in particular Peter Limon, deserves praise for their contributions to this resurgence. It has lead to a strong, coherent national program for the development of superconducting materials and accelerator quality magnets.

Appendix 1:
Charge of the Review Committee

Fermilab

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March 26, 2002

Charge to the Committee
Internal Review of the FNAL Superconducting Magnet Program
April 25-26, 2002

The Superconducting (SC) Magnet Program in the Technical Division (TD) of Fermi National Laboratory (FNAL) has been focused on R&D to develop high and low field accelerator magnets suitable for a future large hadron collider and for upgrades to existing machines. This R&D program and activities related to the construction of high gradient SC IR quads for the LHC serve to maintain Fermilab's core competence in superconducting accelerator magnet technology. Expertise in this area is crucial for providing long-term maintenance and operation of the Tevatron, for developing magnets required for future upgrades of the LHC, and for insuring that the technology is in place in US HEP to construct future large hadron colliders. The FNAL TD also performs materials research aimed at improving Nb3Sn superconductors, cables, and other components required in such magnets.

In your review of this program, please consider the following:

1. In light of the recently released HEPAP sub-panel's twenty-year road map and plans, please evaluate the group's plans. Are the goals relevant as well as realistic? What are their short-term, 3-year and 5-year R&D plans?

2. Please evaluate the recent results of the low-field and high-field accelerator magnets. Are the designs being pursued reasonable? Are test results well understood and documented?

3. Evaluate the plan for TD participation in LHC magnet R&D program aimed at 2nd generation IR quads.

4. Please evaluate progress and prospects in the area of Nb3Sn strand and cable development effort.

5. Is TD management providing the group with adequate facilities and support for reasonable efficiency in conducting the program?

6. Please evaluate the group's staffing, management and resources, now and as it relates to the 3-year and 5-year plan.

7. Assess the size and adequacy of the TD SC magnet organization to provide maintenance and support for Tevatron magnets including design and development efforts for future projects and upgrades.

8. Any other comments or recommendations the committee may have that would improve the prospects for achieving the FNAL program goals and their relationship to the national program would be greatly appreciated.

The committee is requested to prepare a draft report on the final day of the review and share its findings with TD management in a close-out session on that day. The final version of this report including comments and recommendations should be in the form of group report. This document should be sent to Robert Kephart, Head, Technical Division at the address indicated above.

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Appendix 2:
Agenda of the Review

Internal Review of the FNAL Superconducting Magnet Program
April 25-26, 2002

Agenda

April 25

8:30 - 8:45	Welcome and Charge to the Committee	Bob Kephart
8:45 - 9:15	Introduction to the SC Magnet Program	Peter Limon
9:15 - 9:45	SC Magnet Support for the Tevatron	Dave Harding
9:45 - 10:15	LHC Project	Jim Kerby
10:15 -10:30	Break	
10:30 -10:40	High Field Magnet R&D program Overview	Sasha Zlobin
10:40-11:00	High Field Magnet Design Considerations	Vadim Kashikhin
11:00-11:30	Cos-theta Dipole Mechanical design	Deepak Chichili
11:30-12:00	Cos-theta Dipole test results	Sasha Zlobin
12:00-13:00	Lunch & Discussion	
13:00-13:45	Common Coil & Racetrack coil	Giorgio Ambrosio
13:45-14:15	Low Field Magnet R&D	Henryk Piekarz
14:15-14:45	Development, Construction, and Test Resources at Fermilab	Mike Lamm
14:45-16:15	Tour of IBC (LHC), IB3, IB1	all
16:15-16:30	Break	
16:30-17:15	SC Strand and Cable R&D	Emanuela Barzi
17:15-17:45	Discussion/Questions	Committee
17:45-18:15	Executive Session	
19:00	Dinner at Tribella	

April 26

8:30 - 9:00	Executive Session/Writing Assignments	
9:00 - 9:45	Future Plans for SC Magnet Program	Sasha Zlobin
9:45 - 10:30	Questions and discussion	
10:30 - 12:30	Committee Executive Session (writing)	
12:30-13:30	Lunch/Discussion	
14:00-15:00	Closeout	Committee Chair
15:00	End	

HFM R&D program overview

Outlines:

Program goals

Program structure

Budget

Activities

Presentations

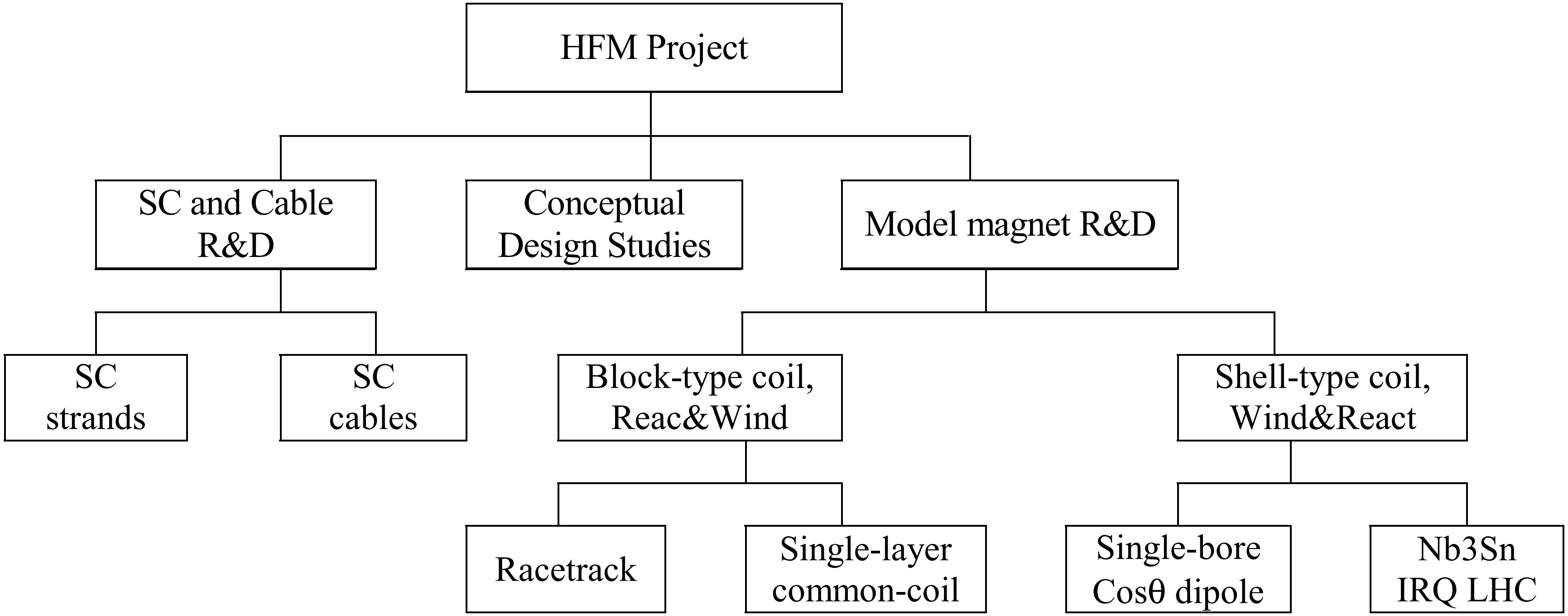
Publications

HFM Program goals

- Development of SC accelerator magnets
  - operating at 4.3-4.5 K
  - with nominal magnetic fields above 10 T
  - with large critical temperature margin
  - for different applications
- Development and study of new SC strands, cables and structural materials
- Development of new cost effective and robust fabrication technologies
- Development of necessary expertise and infrastructure at Fermilab

SC Magnets
at Fermilab

HFM Program structure

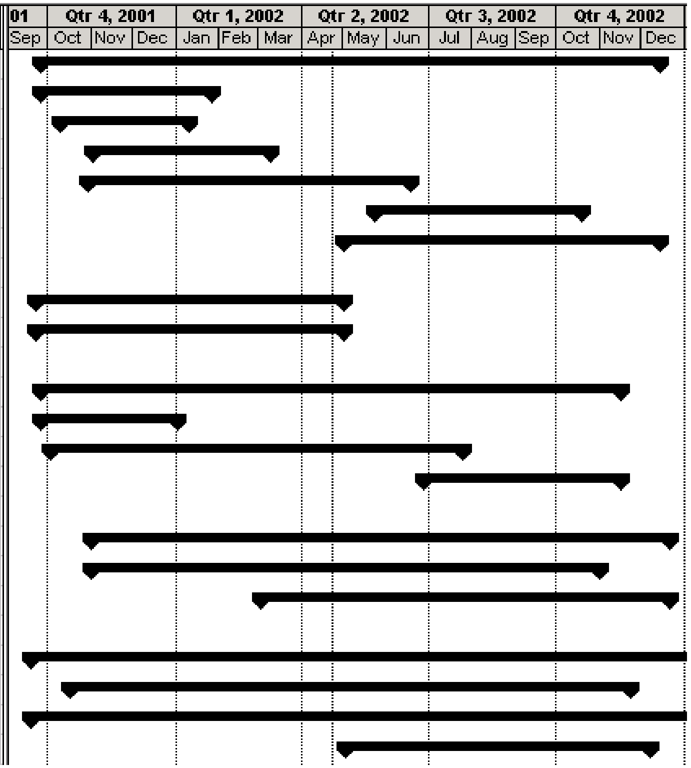


Management

SC Magnets at Fermilab

- Meetings for discussion and coordination efforts, schedule and technical issues:
  - Monday production meeting (IB3)
  - Wednesday working group meeting (ICB)
- MS Project for project schedule monitoring.

Task Name	Duration	Start	Finish
1. COS-THETA DIPOLE MODELS	64w	09/24/01	12/13/02
Splicing Technique	18w	09/24/01	01/25/02
End Design Modification	13.4w	10/08/01	01/08/02
Fabrication Tooling Modification	18.6w	10/31/01	03/08/02
HFDA04	33.1w	10/28/01	06/17/02
HFDA05	21.5w	05/22/02	10/18/02
2-in-1 CosT Dipole Mechanical Model	33w	04/29/02	12/13/02
2. RACETRACKS	31.6w	09/20/01	04/29/02
HFDB02	31.6w	09/20/01	04/29/02
3. COMMON COIL DIPOLE MODELS	60w	09/24/01	11/15/02
Common Coil Mechanical Model	14.2w	09/24/01	12/31/01
Common Coil Technological Model	42.6w	10/01/01	07/24/02
HFDC01	20.6w	06/26/02	11/15/02
4. Nb3Sn QUADRUPOLE MODELS	59.6w	10/30/01	12/19/02
Conceptual Design Study	52.4w	10/30/01	10/30/02
70-mm IRQ model	42w	03/01/02	12/19/02
5. S/C & CABLE R&D	72.4w	09/17/01	02/04/03
Cabling Machine Modifications	58w	10/15/01	11/22/02
Strand procurement and tests	72.4w	09/17/01	02/04/03
Nb3Sn cable fabrication and tests	31.6w	05/01/02	12/06/02



HFM Program budget

- Man-power summary

	1998	1999	**2000**	2001	2002
TECH	0	1	**4**	5	5.5
EDIA	0.2	0.8	**12**	13.8	18.1
Total	0.2	1.8	**16**	18.8	23.6

- Budget summary

	1998	1999	**2000**	2001	2002
SWF, k$	16	118	**1,237**	1,481	2,003
M&S, k$	350	742	855	753	975

SC Magnets at Fermilab

Summary of activities

	1998	1999	2000	2001	2002
CDS			VLHC, Tevatron	VLHC, LHC IR upgrade, Tevatron	LHC IR upgrade, Tevatron
Cos-theta	DS, Infrastructure	DS, Tooling, MM50mm	MM43mm, HFDA01	HFDA02, HFDA03	HFDA04, HFDA05
Common coil		CDS	DS, Tooling	CCMM, HFDB01	HFDB02, HFDC01
Nb3Sn IRQ					DS of 70-mm IRQ/MQXB
Nb3Sn strands	20kg	210kg	247kg	304kg	158kg+180kg
SC R&D	Ovens, Teslatron, Ic tests	Magnetiz. meas., short sample tests (SST)	SST, microstructure studies (MS)	Optical microscope, SEM, SST, MS	SST, MS
Cable R&D			Cable tests (NHFML)	Cable tests (NHFML), cabling machine (CM), cable fabrication (CF)	CM upgrade, SC transformer, CF

DS – design study; CDS – conceptual design study; MQXB – NbTi quad for the LHC IRs; SEM – scanning electron microscope; MM – mechanical models; HFDA – cos-theta dipole models; HFDB – racetracks; HFDC – common coil dipole models

Presentations

- Program reviews: twice per year by AAC since 1999
- Presentations at VLHC workshops, Snowmass2001, LHC collaboration meeting, LTSC Workshops
- Conferences

	1998	1999	2000	2001	2002
PAC	-	2	-	9	-
EPAC	-	-	-	-	4
ASC	-	-	13	-	18
MT	-	9	-	6	-
CEC/ICMC	-	1	-	5	-
Others	-	-	1	1	?

Publications (summary)

- Number of publications

	1998	1999	2000	2001	2002
Papers	-	12	14	21	21
TD notes	12	31	33	44	7
Laurea Thesis	-	-	1	1	1
PhD Thesis	-	-	-	-	1

- Publication topics

	1998	1999	2000	2001	2002
CDS	-	1	2	6	3
HFM Models	-	8	7	8	12
SC & Cable	-	3	5	5	5
Accelerators	-	-	-	2	1

Publication list

1. G. Ambrosio et al., "Conceptual Design of the Fermilab Nb_3Sn High Field Dipole Model", 1999 Particle Accelerator Conference, New York, Proceedings, March 1999, pp. 174-176.
2. D.R. Chichili et al., "Niobium-Tin Magnet Technology Development at Fermilab", 1999 Particle Accelerator Conference, New York, Proceedings, March 1999.
3. E. Barzi et al., "Study of Strand Critical Current Degradation in a Rutherford Type Nb_3Sn Cable", CEC'99, Montreal (Canada), July 1999.
4. G. Ambrosio et al., "Conceptual Design Study of High Field Magnets for Very Large Hadron Collider", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.310.
5. G. Ambrosio et al., "Conceptual Design of a Common Coil Dipole for VLHC", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.330.
6. G. Ambrosio et al., "Development of the 11 T Nb_3Sn Dipole Model at Fermilab", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.298.
7. G. Ambrosio et al., "Magnetic Design of the Fermilab 11 T Nb_3Sn Short Dipole Model", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.322.
8. G. Ambrosio at al., "Mechanical Design and Analysis of the Fermilab 11 T Nb_3Sn Dipole Model", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.306.
9. G. Ambrosio et al., "Study of the React and Wind Technique for a Nb3Sn Common Coil Dipole", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.338.
10. N. Andreev et al., "Fabrication and Testing of High Field Dipole Mechanical Model", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.314.
11. E. Barzi et al., "Heat Treatment Study of Nb_3Sn Strands for the Fermilab's High Field Dipole Model", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.1000.
12. D. R. Chichili, et al., "Investigation of Cable Insulation and Thermo-Mechanical Properties of Epoxy Impregnated Nb_3Sn Composite", *MT-16,* Tallahassee, FL, Sept. 1999. IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, p.1317.

SC Magnets
at Fermilab

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13. D.R. Chichili et al., "Fabrication of the Shell-Type Nb3Sn Dipole Model at Fermilab", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2160.
14. V.V. Kashikhin and A.V. Zlobin, "Magnetic Designs of 2-in-1 Nb3Sn Dipole Magnets for VLHC", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2176.
15. V.V. Kashikhin and A.V. Zlobin, "Correction of the Persistent Current Effect in Nb3Sn Dipole Magnets", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2058.
16. D.R. Chichili et al., "Mechanical Design and Analysis of Fermilab 2-in-1 Shell-Type Nb3Sn Dipole Models", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2288.
17. I. Novitski et al., "Design and Mechanical Analysis of a Single-Layer Common Coil Dipole for VLHC", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2276.
18. G. Ambrosio et al., "Development of React & Wind Common Coil Dipoles for VLHC", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2172.
19. R. Yamada et al., "Design and Considerations on Long Nb3Sn High Field Magnets for Hadron Colliders", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2054.
20. S. Yadav et al., "Coil Design Issues for the High Field Dipole at Fermilab", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2284.
21. P. Bauer et al., "Fabrication and Testing of Rutherford-Type Cables for React and Wind Accelerator Magnets", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2457.
22. E. Barzi et al., "Study of Nb3Sn Strands for Fermilab's High Field Dipole Models", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 3595.
23. E. Barzi et al., "Strand Critical Current Degradation in Nb3Sn Rutherford Cables", ASC'2000, Virginia Beach, VG, Sept. 2000. IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2134.
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27. "Design study for a staged Very Large Hadron Collider", Fermilab-TM-2149, June 4, 2001.
28. T. Sen, J. Strait, A.V. Zlobin, "Second Generation High Gradient Quadrupoles for the LHC Interaction Regions", RPPH083, PAC'01, Chicago, IL, June 2001.
29. A.V. Zlobin, G. Ambrosio, N. Andreev, E. Barzi, D. Chichili, V.V. Kashikhin, P.J. Limon, I. Terechkine, S. Yadav, R. Yamada, "Development of cos-theta Nb3Sn dipole magnets for VLHC", RPPH085, PAC'01, Chicago, IL, June 2001.
30. N. Andreev, D. Chichili, C. Christensen, J. DiMarco, V.V. Kashikhin, P. Schlabach, C. Sylvester, I. Terechkine, J.C. Tompkins, G. Velev, A.V. Zlobin, "Field quality of the Fermilab Nb3Sn high field dipole model", RPPH082, PAC'01, Chicago, IL, June 2001.
31. V.V. Kashikhin, A.V. Zlobin, "Single-layer high field dipole magnets", RPPH081, PAC'01, Chicago, IL, June 2001.
32. V.V. Kashikhin, A.V. Zlobin, "Nb3Sn arc quadrupole magnets for VLHC", RPPH080, PAC'01, Chicago, IL, June 2001.
33. G. Ambrosio, N. Andreev, E. Barzi, P. Bauer, D. Chichili, K. Ewald, L. Imbasciati, V.V. Kashikhin, P. Limon, I. Novitsli, J.M. Rey, R. Scanlan, S. Yadav, R. Yamada, A.V. Zlobin, "Design and development of Nb3Sn single-layer common coil dipole magnet for VLHC", RPPH079, PAC'01, Chicago, IL, June 2001.
34. L. Imbasciati, P. Bauer, G. Ambrosio, V. Kashikhin, M. Lamm, A.V. Zlobin, "Quench protection of high field Nb3Sn magnets for VLHC", RPPH095, PAC'01, Chicago, IL, June 2001.
35. P. Bauer, C. Darve, P. Limon, I. Terechkine, N. Solyak, M. Pivi, W.C. Turner, S. Sharma, "Synchrotron Radiation Issues in the VLHC", Proceedings of the 2001 Particle Accelerator Conference, Chicago, June 2001
36. M. Pivi, W.C. Turner, P. Bauer, P. Limon, "Synchrotron Radiation and Beam Tube Vacuum in a Very Large Hadron Collider, Stage 1 and Stage 2 VLHC", Proceedings of the 2001 Particle Accelerator Conference, Chicago, June 2001

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SC Magnets at Fermilab

37. J.-M. Rey, E. Barzi, S. Mattafirri, J. Hoffman, R. Yamada, "Effect of Partially Reacting Nb_3Sn Before Magnet Winding on the Strand Critical Current", Proceedings of the Cryogenic Engineering and International Cryogenic Materials Conference, Jul. 16-20, 2001, Madison, WI.
38. E. Barzi, G. Ambrosio, M. Fratini, P. Bauer, R.M. Scanlan, R. Yamada, A.V. Zlobin, "Study of Nb3Sn strands and cables for Fermilab's common coil dipole models", CEC/ICMC'01, Madison, WI, July 2001.
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40. E. Barzi, M. Fratini, A.V. Zlobin, "A device to test critical current sensitivity of Nb3Sn cables to pressure", CEC/ICMC'01, Madison, WI, July 2001.
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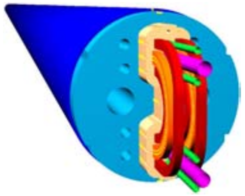
42. V.V. Kashikhin, A.V. Zlobin, "Magnetic designs and field quality of Nb3Sn accelerator magnets", MT-17, Geneva, Switzerland, Sept. 2001.
43. N. Andreev et al., "Development and test of single-bore cos-theta Nb3Sn dipole models with cold iron yoke", MT-17, Geneva, Switzerland, Sept. 2001.
44. N.I. Andreev, D.R. Chichili, I.M. Terechkine, A.V. Zlobin, "Development and study of insulation systems for Nb3Sn accelerator magnets", MT-17, Geneva, Switzerland, Sept. 2001.
45. E. Barzi et al., "Superconductor and cable R&D for high field accelerator magnets at Fermilab", MT-17, Geneva, Switzerland, Sept. 2001.
46. G. Ambrosio et al., " R&D for a single-layer Nb3Sn common coil dipole using the react-and-wind fabrication technique", MT-17, Geneva, Switzerland, Sept. 2001.
47. P. Bauer, M. Dietrich, G.W. Foster, V.V. Kashikhin, P.J. Limon, V. Shiltsev, N. Solyak, "The influence of accelerator physics on the magnet design of a Very Large Hadron Collider", MT-17, Geneva, Switzerland, Sept. 2001.

SC Magnets
at Fermilab



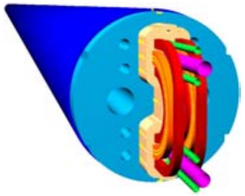
HFM Design Considerations

Outline of presentation:

- Magnet R&D goals
- Typical design steps
- Magnet design tools
- VLHC magnets
- Quadrupole for the LHC IR upgrade
- TEVATRON LBQ magnet
- Conclusions

SC Magnets
at Fermilab

Magnet R&D goals



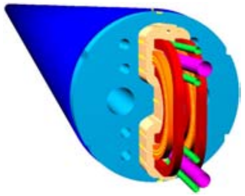
- **Long term:** **development of economically effective and innovative designs of Nb_3Sn dipole and quadrupole magnets for a future Very Large Hadron Collider.**

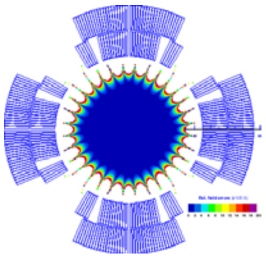
- **Medium term:** **development of the IR quadrupole magnets for LHC luminosity upgrade.**

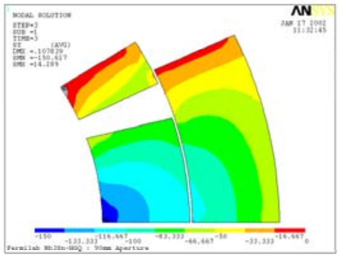
- **Short term:** **development of the spare LBQ magnets for the use in TEVATRON.**

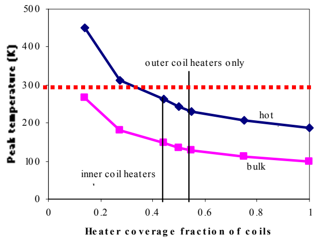
SC Magnets
at Fermilab

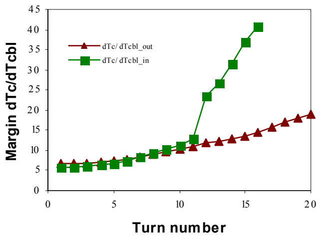
Typical design steps







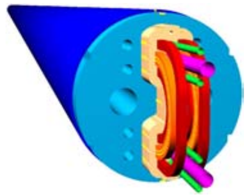




- **Magnetic design and optimization:**
  - o **Field quality within 10^{-4};**
  - o **Peak field point is within the straight section;**
  - o **Sufficient field margin;**
  - o **Minimum coil and yoke cross-section.**
- **Structural analysis:**
  - o **Coils are compressed during operation;**
  - o σ_{coil} **< 150 Mpa,** $\sigma_{material} < \sigma_{yield}$;
  - o δ_{turns} **< 100 μm.**
- **Quench protection:**
  - o **Peak temperature in coil < 300 K;**
  - o **Peak voltage in coil < 1000 V.**
- **Thermal analysis:**
  - o **Effective heat transfer;**
  - o **Sufficient temperature margin.**

SC Magnets
at Fermilab

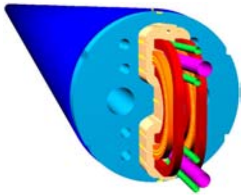
Magnet design tools



- **ROXIE:** (CERN) — **Optimization of the coil cross-sections, inverse field calculations and coil end design.**
- **BEND:** (FNAL) — **Coil end design. Minimization of mechanical stresses during coil winding.**
- **QLASA:** (INFN) — **Quench protection analysis. Temperature and voltage calculation across the coil.**
- **Quench Pro:** (FNAL) — **Quench protection analysis. Temperature and voltage calculation across the coil.**
- **OPERA:** (Vector Fields) — **2D and 3D analysis of magnetic fields. Used for the iron yoke optimization and final coil tuning.**
- **ANSYS:** (ANSYS Inc.) — **2D and 3D mechanical analysis. Used for the structural and thermal simulations.**

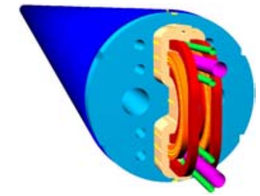
SC Magnets
at Fermilab

VLHC magnets



Target parameters

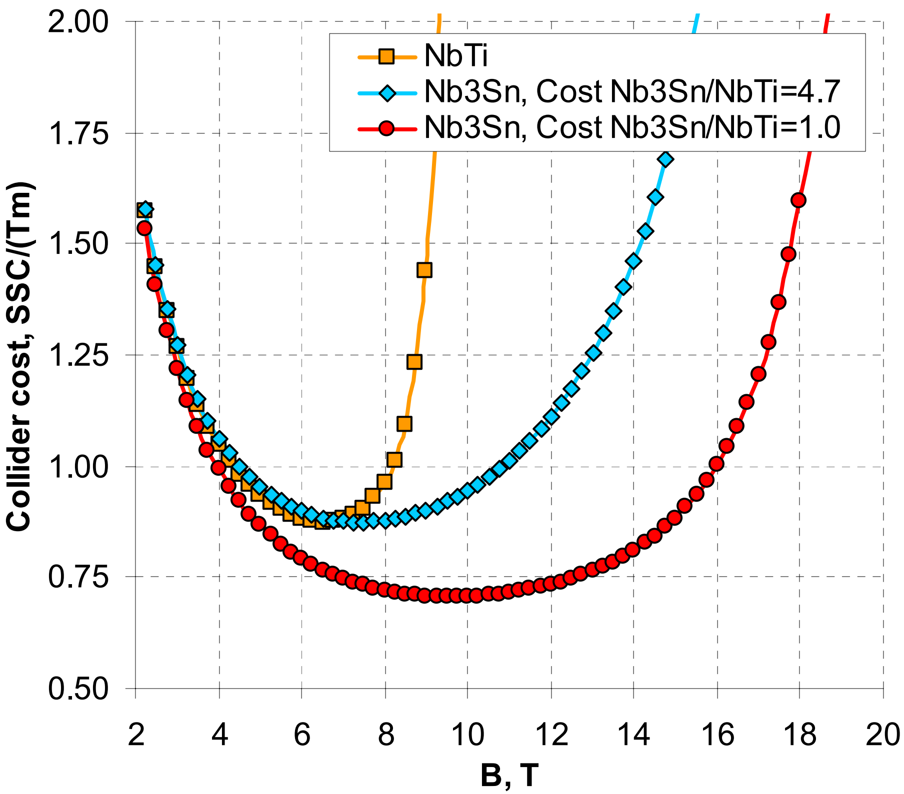
- **Minimum cost → optimum field, aperture and superconductor;**
- **Geometrical field quality meets the field error table;**
- **Yoke saturation effect < 10^{-4};**
- **Coil magnetization effect is smaller than in NbTi magnets;**
- **Operating temperature 4.5-5.5 K;**
- **Sufficient operating margins;**
- **Horizontal or vertical bore orientation.**

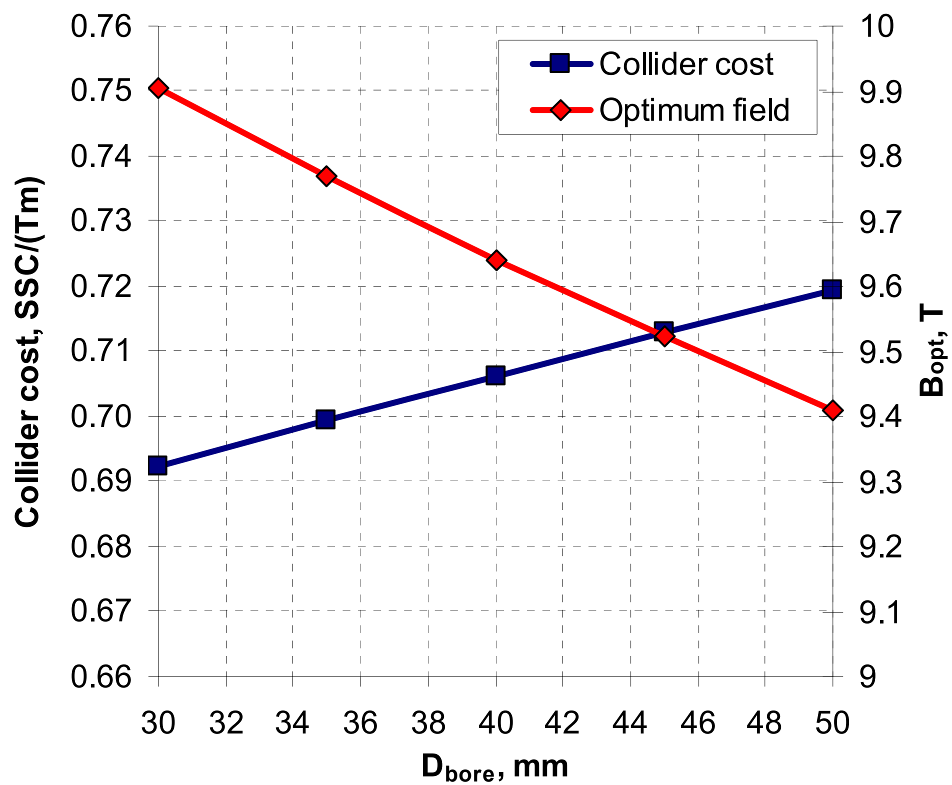


SC Magnets at Fermilab

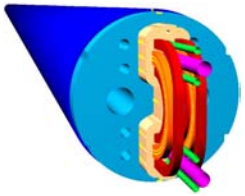
VLHC magnets

Optimum field



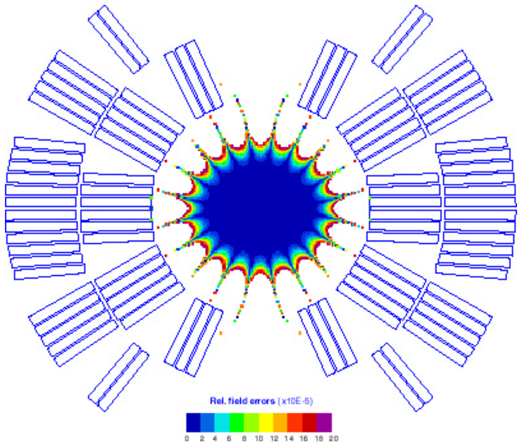


Nb_3Sn superconductor, Optimum field → 10 T, Aperture > 40 mm

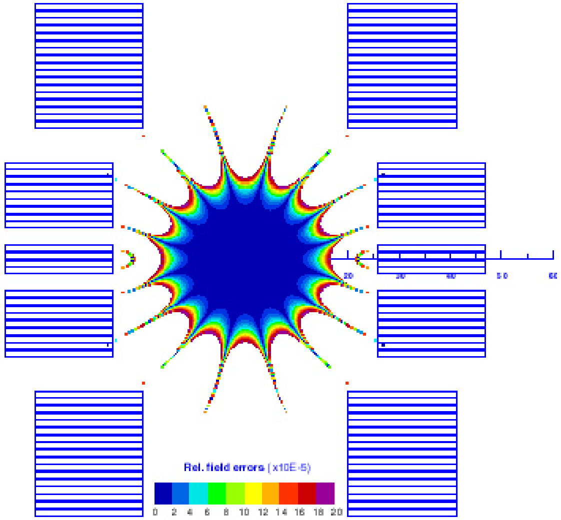


VLHC magnets

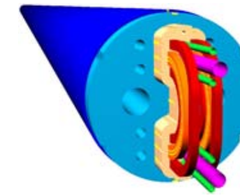
Dipole coil optimization



- **Shell type coil:**
  - **Traditional two-layer design;**
  - **Geometrical field quality within 10^{-5};**
  - **Minimized coil volume.**

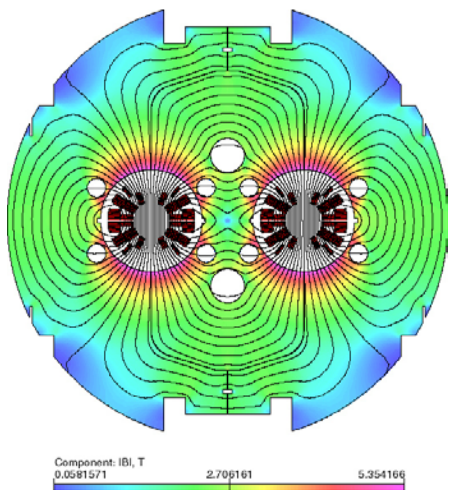


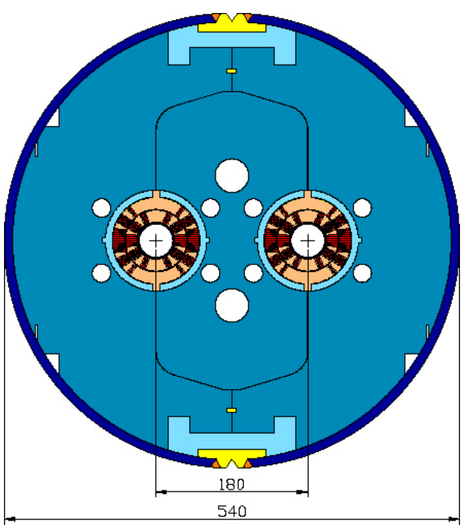
- **Block type coil:**
  - **Innovative single-layer design with small number of blocks;**
  - **Geometrical field quality within 10^{-5};**
  - **Well suited for the "react and wind" approach in the common coil configuration.**



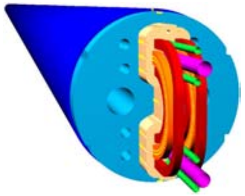
VLHC magnets

Dipole yoke optimization I

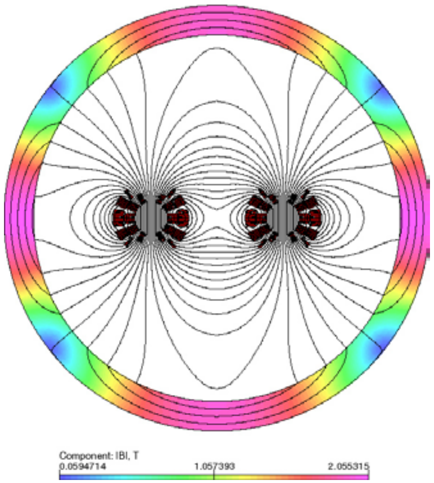


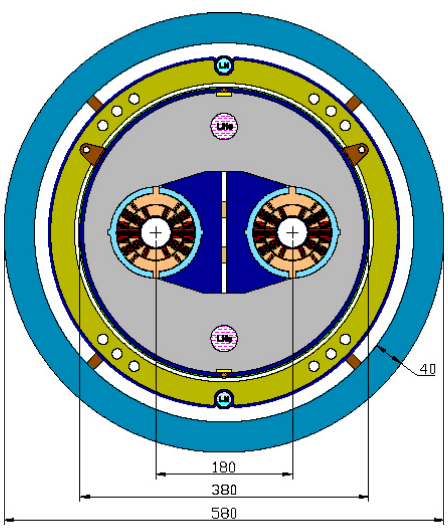


- **Shell type dipole with "cold" yoke:**
  - **Minimized yoke size and bore separation;**
  - **Yoke saturation effect within 10^{-4};**
  - **Gap parallel to a flux line minimizes the field distortions;**
  - **No collars, prestress is provided by the yoke and outer skin.**



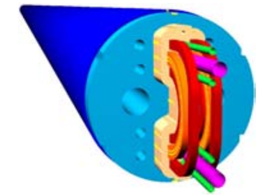
Dipole yoke optimization II



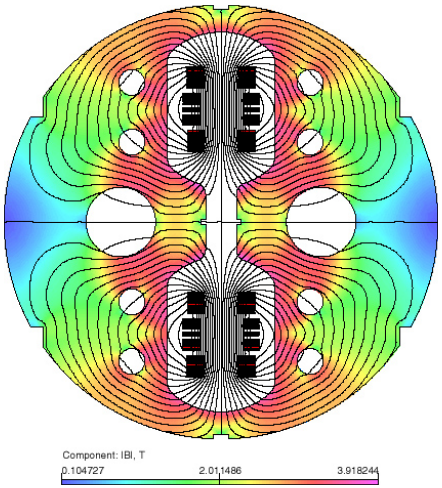


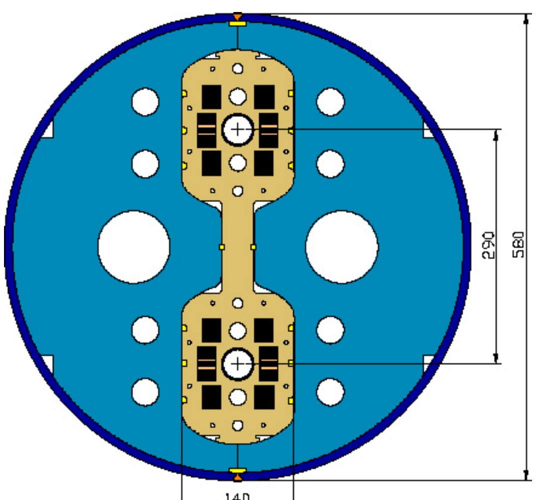
- **Shell type dipole with "warm" yoke:**
  - **Innovative compact design;**
  - **Exceptionally low magnet size and weight;**
  - **Yoke saturation effect within 10^{-4};**
  - **Coils are constrained within common aluminum or stainless-steel structure.**

VLHC magnets



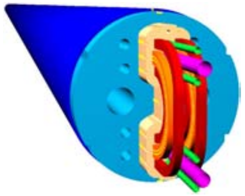
Dipole yoke optimization III



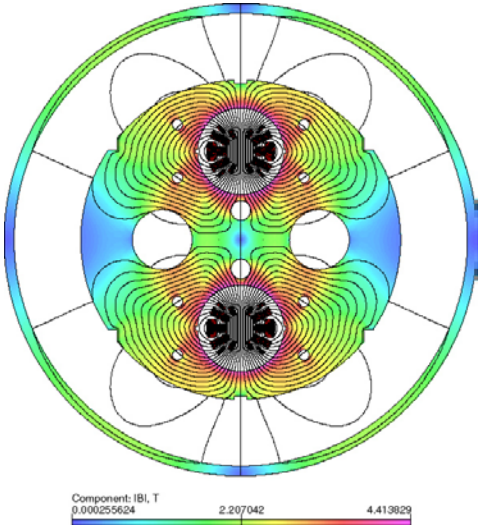


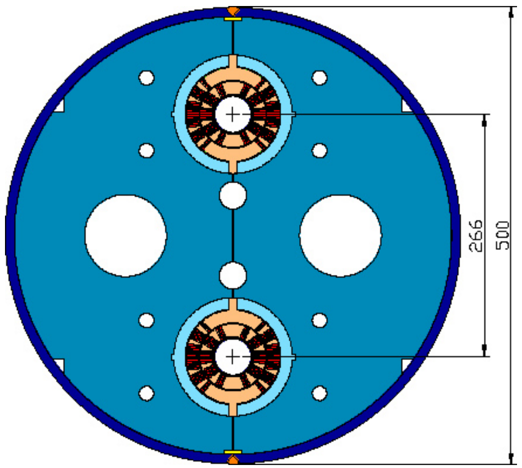
❖ **Common coil dipole magnet:**

- **Bore separation optimized for the "react and wind" technique;**
- **Yoke saturation effect within 10^{-4};**
- **Common collars provide stress management and used as coil winding structure.**



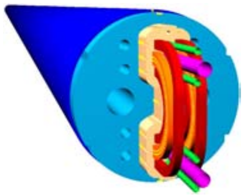
Dipole yoke optimization IV



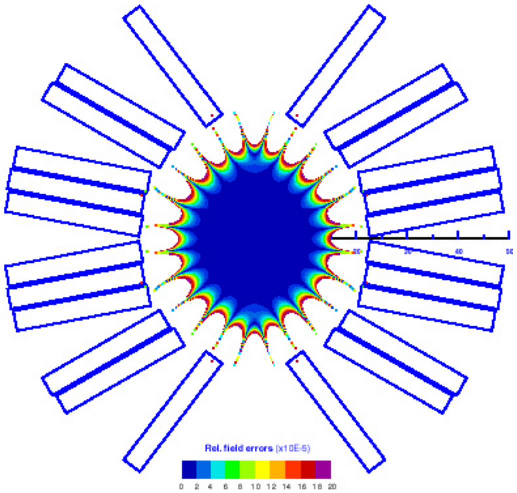


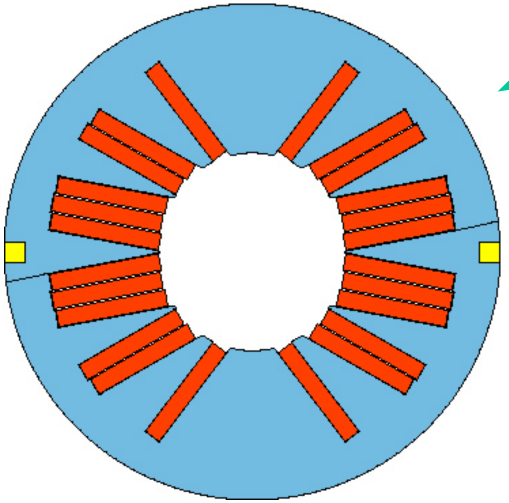
- **Shell type dipole with "cold/warm" yoke:**
  - **Minimized size and weight of the "cold" block;**
  - **Yoke saturation effect within 10^{-4};**
  - **Mechanics is similar to the shell type magnet with horizontal aperture separation.**

VLHC magnets

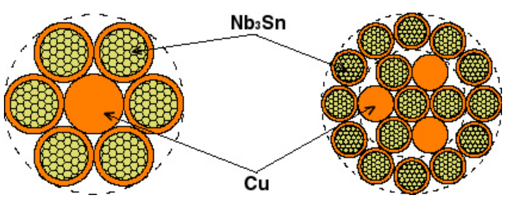


Low-inductance dipole coil I



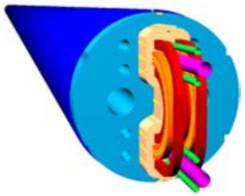


- **Shell type dipole coil:**
  - o **Single-layer design with low inductance;**
  - o **Minimum number of turns;**
  - o **Geometrical field quality within 10^{-5};**
  - o **Wound into the collar structure.**

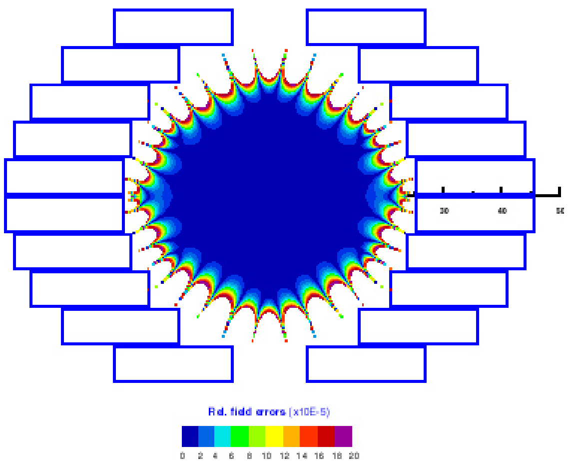


Strand cost savings 15-20 %

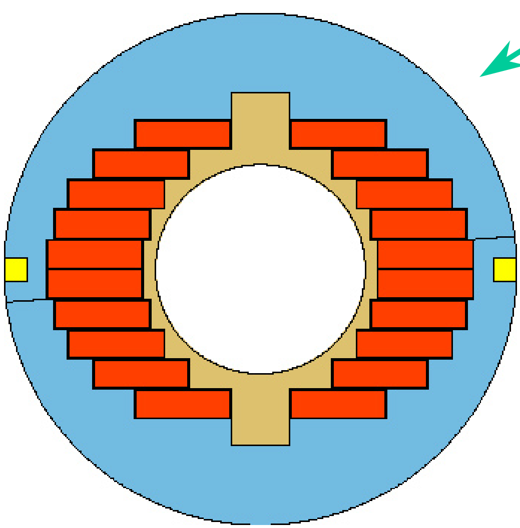
VLHC magnets

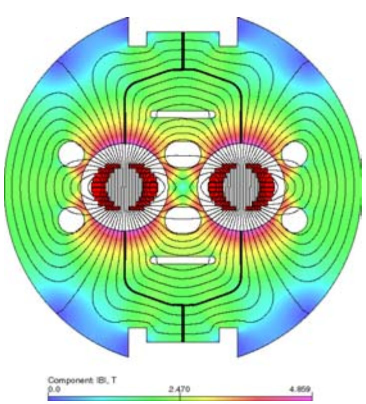


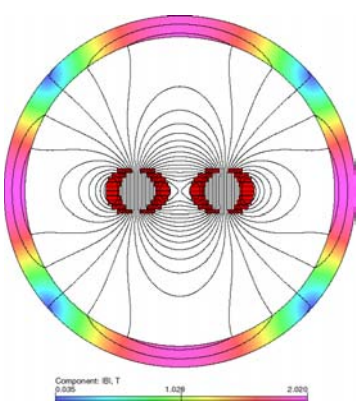
Low-inductance dipole coil II

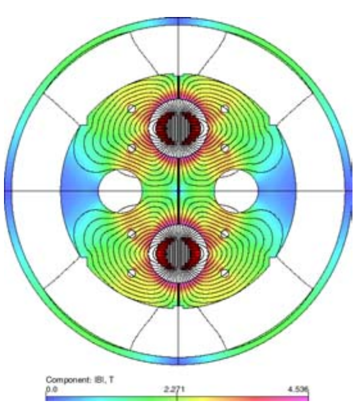


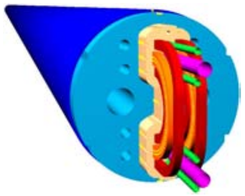
- **Block type dipole coil:**
  - **Single-layer design with low inductance;**
  - **Minimum number of turns;**
  - **Geometrical field quality within 10^{-6};**
  - **Wound into the collar structure;**
  - **Well suited for the common coils configuration.**





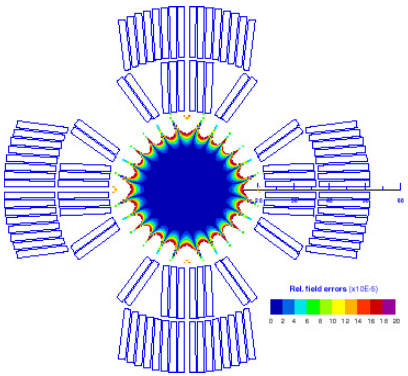


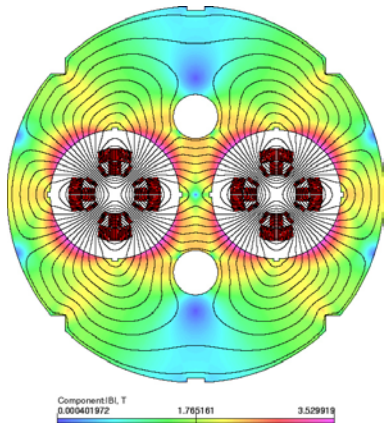


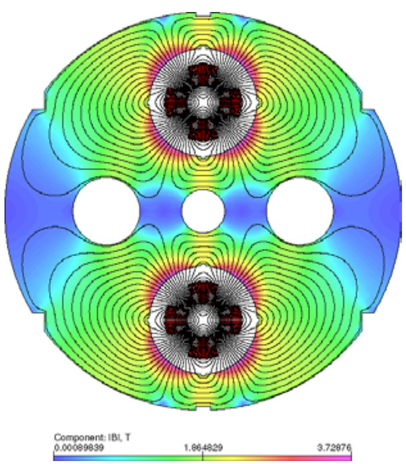


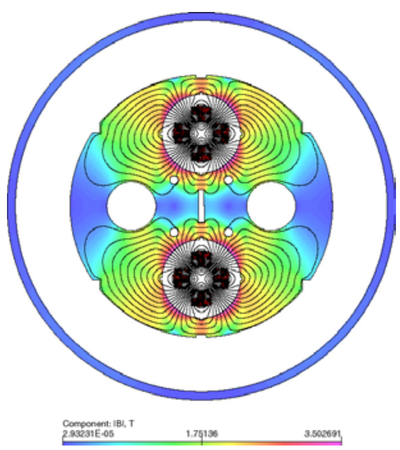
VLHC magnets

Quadrupole optimization

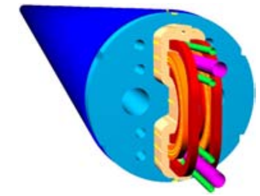








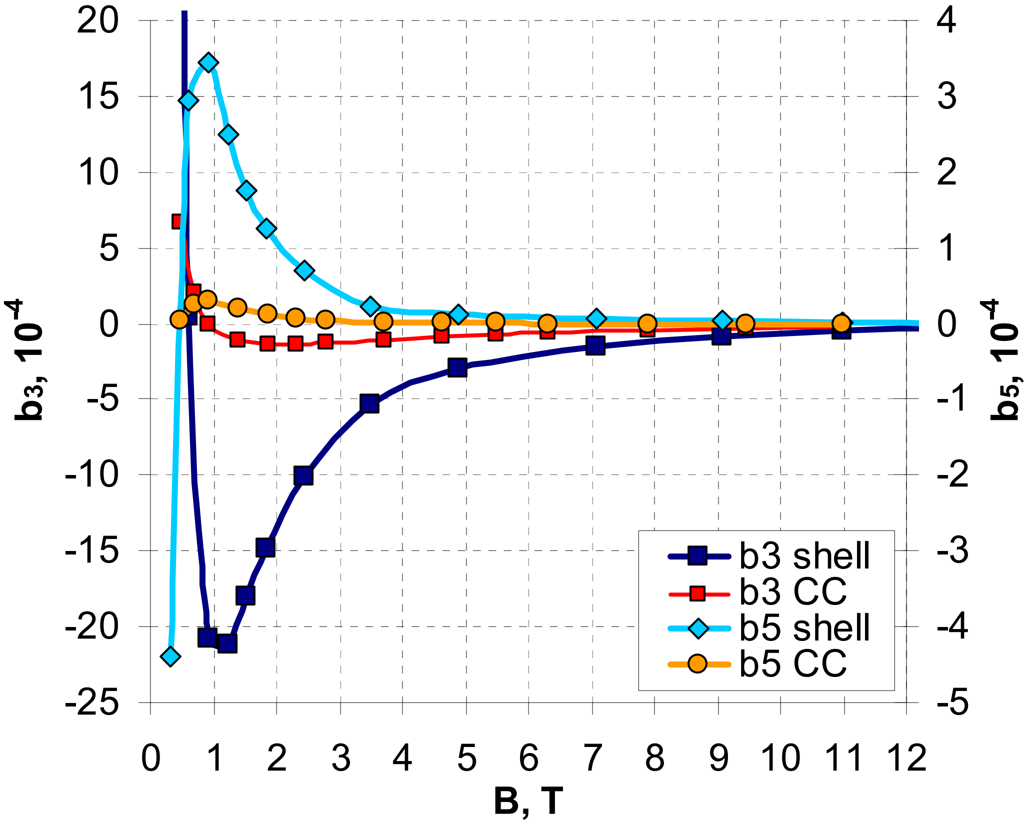
- **All quadrupole magnets meet VLHC target parameters.**
- **Quadrupole with FD functions:**
  - **Works with the horizontal bore dipoles with the "cold" or "warm" iron yoke;**
  - **Positive coupling imposes the minimum yoke size.**
- **Quadrupoles with FF functions:**
  - **Works with the vertical bore common-coil and shell type dipoles;**
  - **Negative coupling and large bore separation increase the yoke size.**



SC Magnets at Fermilab

VLHC magnets

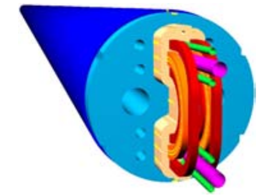
Coil magnetization effect



- **Calculations done using OPERA2D code for the measured SC properties;**
- **Field deviations in the shell type dipole magnets are within (20-30)·10^{-4};**
- **Field deviations in the common coil dipole magnet are within (1.5-2)·10^{-4};**
- **Field deviations in the quadrupole magnets are within (5-7)·10^{-4}.**

It is due to large D_{eff} and J_c in Nb_3Sn strands

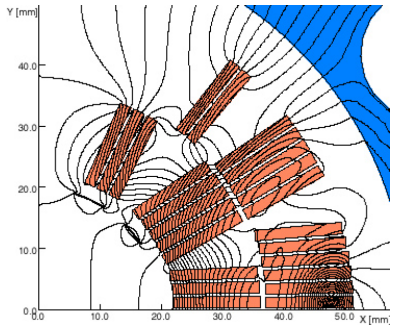
IT HAS TO BE CORRECTED

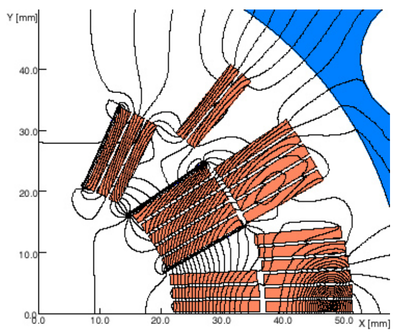


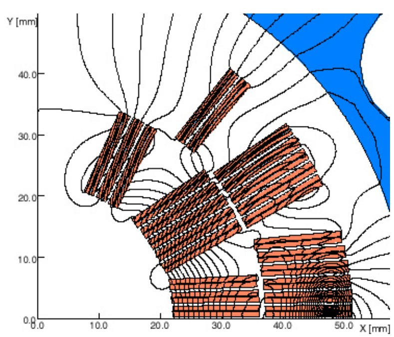
SC Magnets
at Fermilab

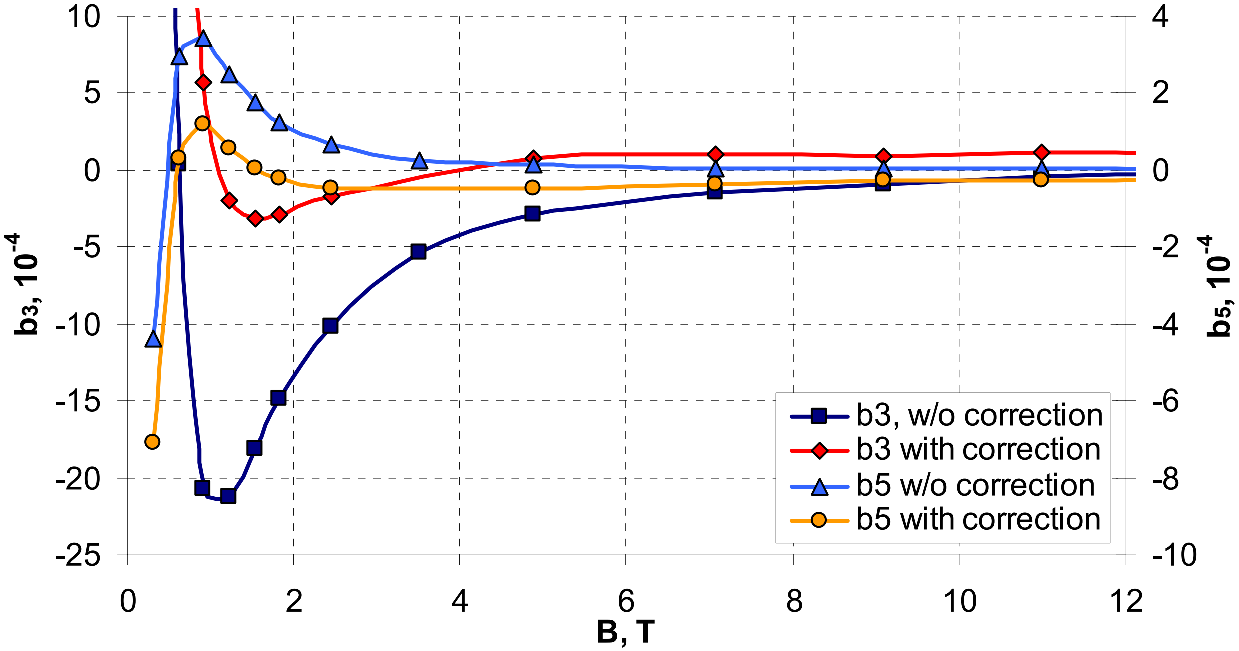
VLHC magnets

Correction of the coil magnetization









- **Simple and inexpensive passive correction:**
  - o **Iron strips inside the aperture;**
  - o **Iron strips on the coil wedges;**
  - o **Iron core inside the cable;**
  - o **All the developed methods are effective;**
  - o **Work for dipole and quadrupole magnets.**

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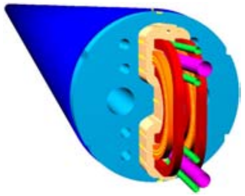
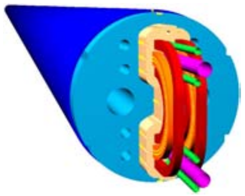
Quadrupole for the LHC IR upgrade



Target parameters

- **90 mm aperture;**
- **200-205 T/m nominal gradient;**
- **Field quality meets current LHC IR specification;**
- **Sufficient field and temperature margin → Nb_3Sn conductor;**
    - **Should fit in the High Gradient Quadrupole cryostat;**
    - **Nominal current < 15 kA;**
    - **Operating temperature 1.9 K or 4.5 K.**

Quadrupole for the LHC IR upgrade



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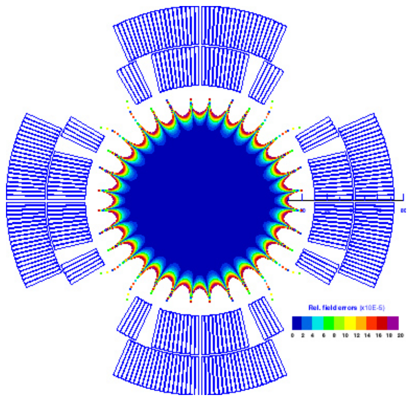
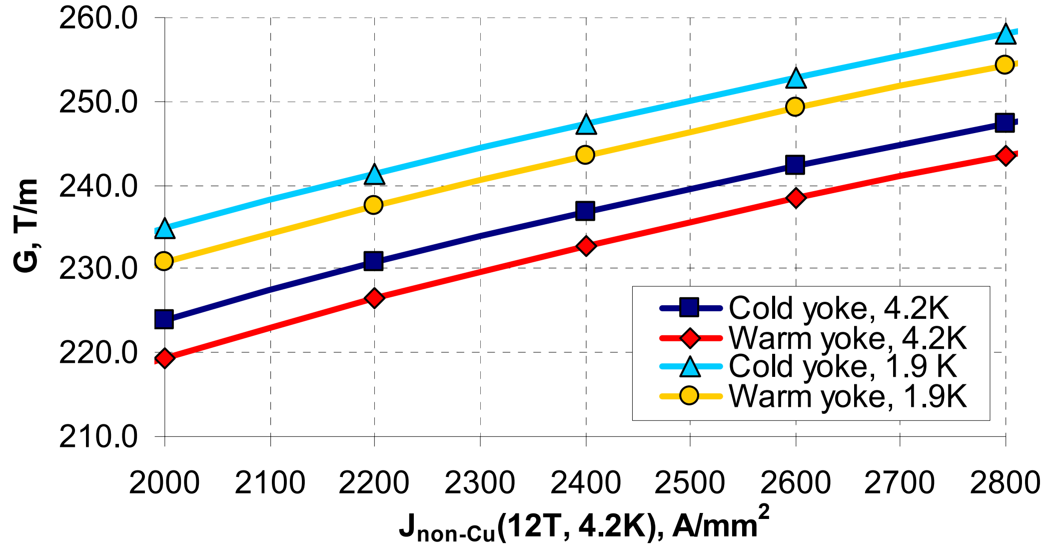
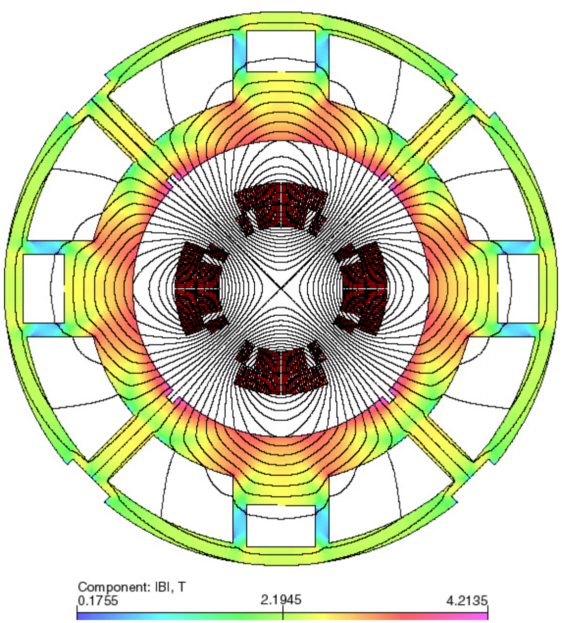
90-mm design







❖ **Magnet features:**

- o **Cable keystoning is close to the ideal;**
- o **Economical 3-block design;**
- o **Nominal gradient 200-205 T/m;**
- o **Geometrical field quality is within 10^{-5};**
- o **Yoke saturation effect is within 10^{-4};**
- o **The same yoke OD as in HGQ;**
- o **Large cooling holes.**

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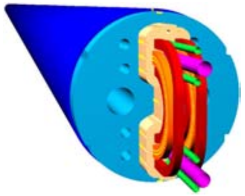
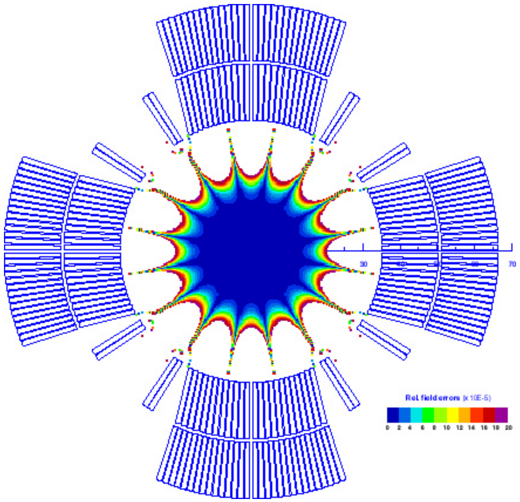
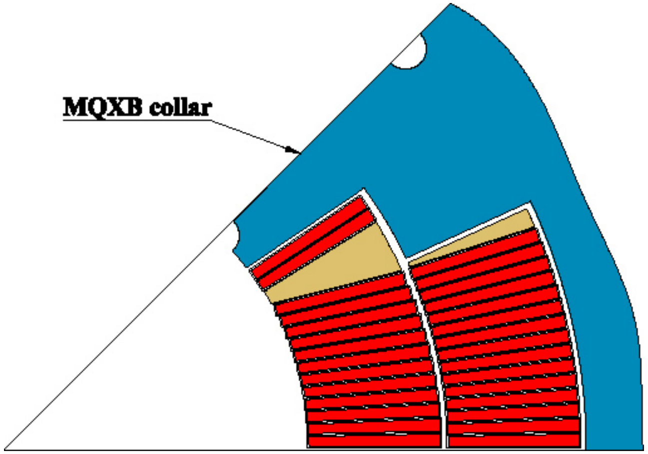
Quadrupole for the LHC IR upgrade



First step - 70-mm design





- **Easy R&D start - using of HGQ collars:**
  - **Collars, iron laminations, skin and assembly tooling are readily available;**
  - **70-mm Nb_3Sn coil fits into HGQ collar;**
  - **Simplified 3-block geometry;**
  - **Maximum gradient 280 T/m;**
  - **Geometrical field quality is within 10^{-4}.**

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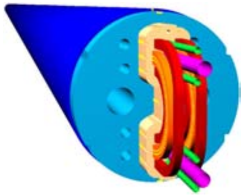
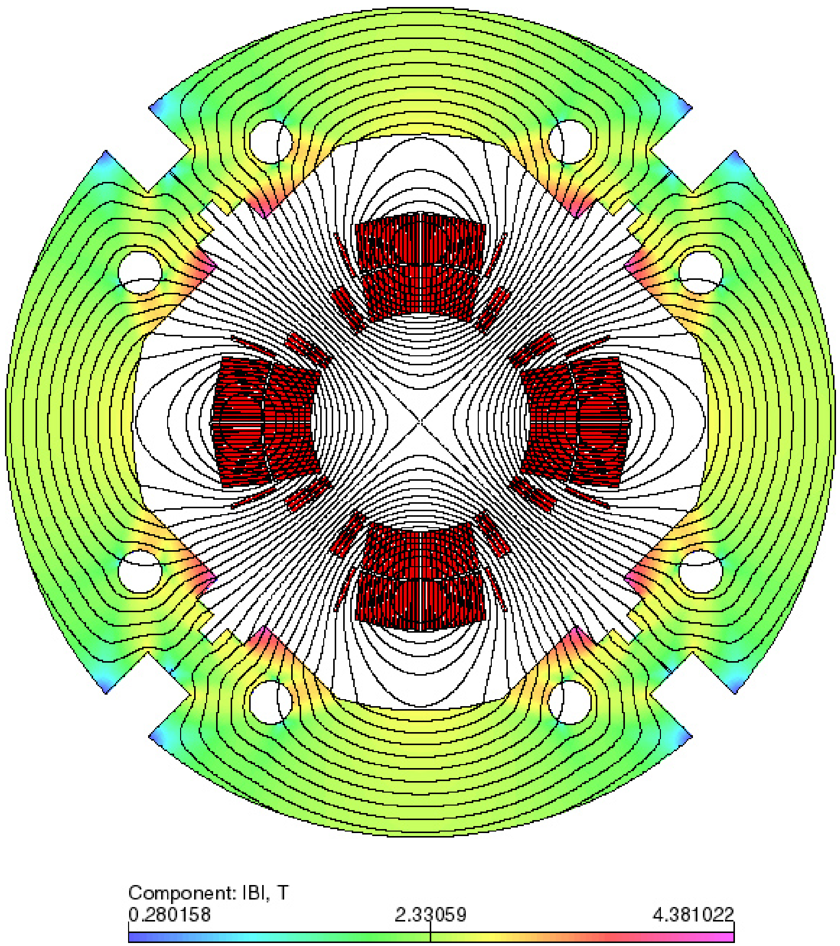
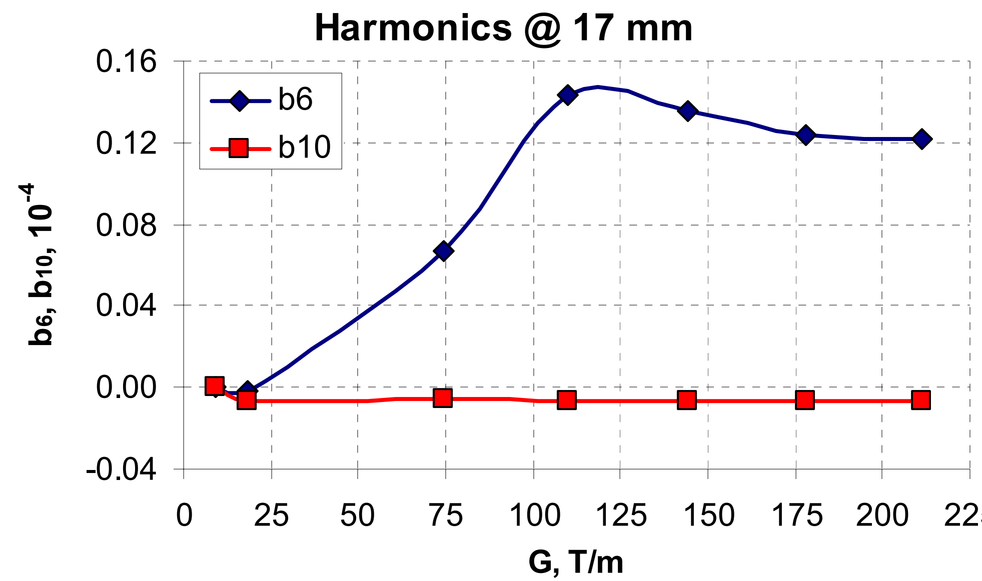
TEVATRON LBQ magnet



Possible LBQ design with HGQ coil

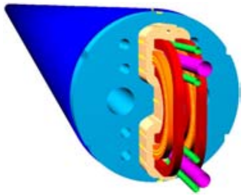




❖ **Magnet features:**

- **HGQ NbTi coil and collar;**
- **70 mm bore diameter;**
- **180 T/m nominal gradient at 4.5 K;**
- **Saturation effect is within 10^{-5};**
- **Yoke OD as in TEVATRON LBQ.**

CONCLUSIONS



- **Innovative high field dipole and quadrupole magnet designs, meeting the VLHC requirements have been developed. Short models of the two-layer shell and single-layer common coil magnets are being fabricated and tested.**

- **Analysis of the quadrupole magnets for the LHC IR upgrade is in progress. The 70-mm design can benefit from most of the available HGQ parts and equipment. The 90-mm magnet will be based on the results of the 70-mm short model R&D.**

- **Modified NbTi HGQ design can be used in the TEVATRON interaction region. Alternative NbTi and Nb_3Sn designs with larger apertures can be developed.**

Design and Fabrication of Nb_3Sn Cos(θ) Dipole Models

Deepak Chichili

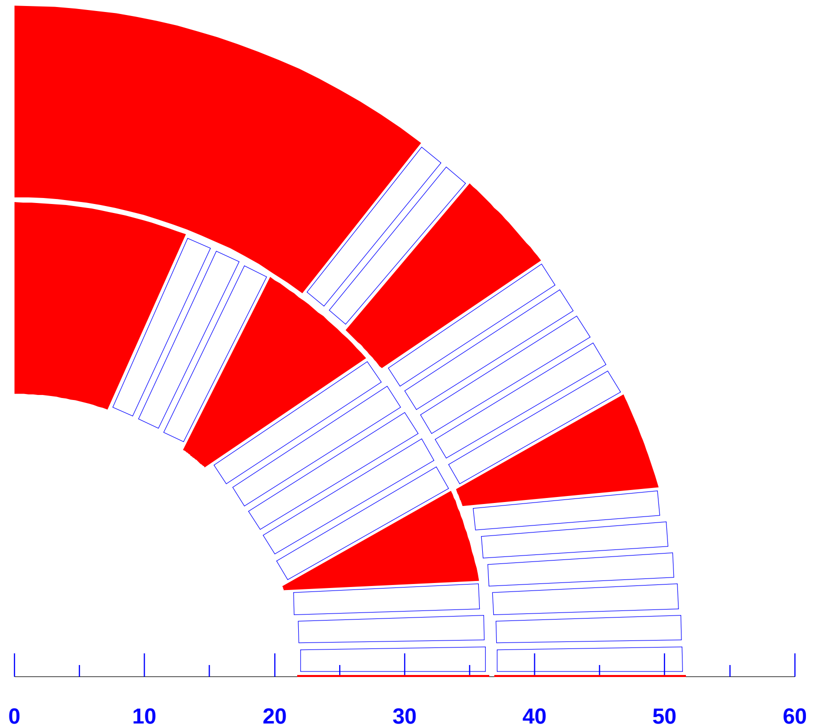
Outline

- **Magnet Design & Technology Overview**
  - **Mechanical Design**
  - **Fabrication**

- **Discussion on the first three Dipole Models**
  - **Observations**
  - **Post-mortem Analysis**
  - **Design & Tooling Modifications**

- **Current Model, HFDA-04**
  - **Fabrication Status**

Design Overview: Magnetic Design



- Magnet bore diameter: 43.5 mm
- Number of Turns: 48
- Strand: Nb_3Sn, ϕ 1.00 mm,
- Jc(12T;4.2K) = 1.8 - 1.9 kA/mm^2
- Bore Field, B = 11- 12 T
- Cable: N=28, 1.80*14.24 mm (keystone)
- Insulation thickness: 250 μm
- Pole Width: 15.09 mm

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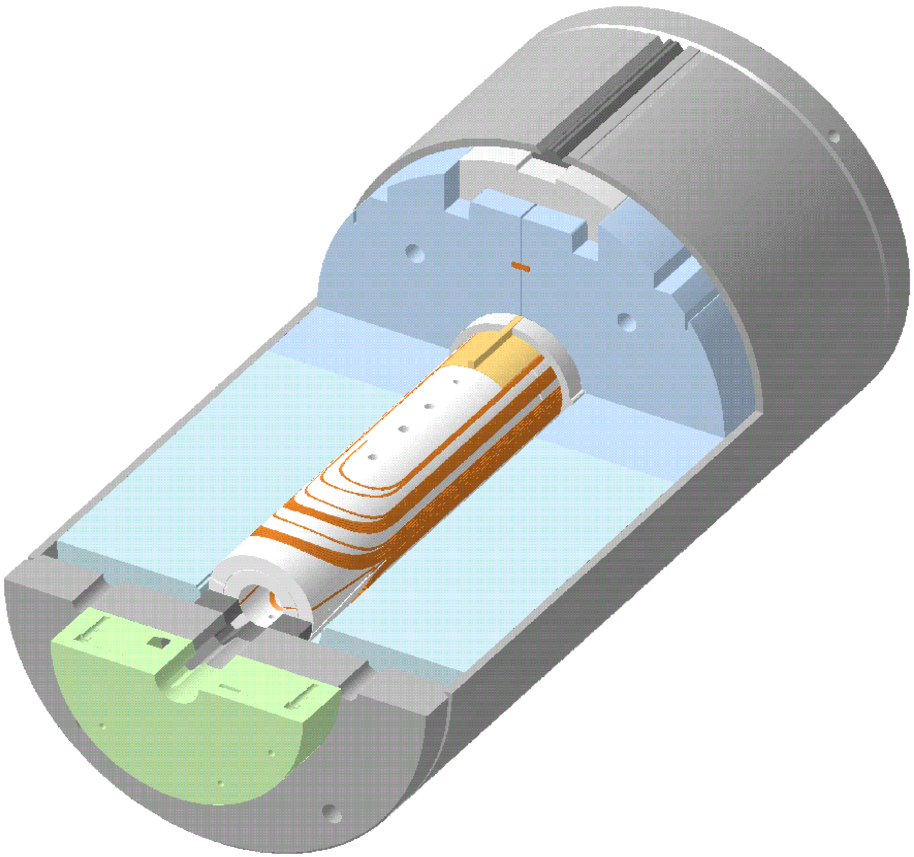
Design Overview: Mechanical Support Structure

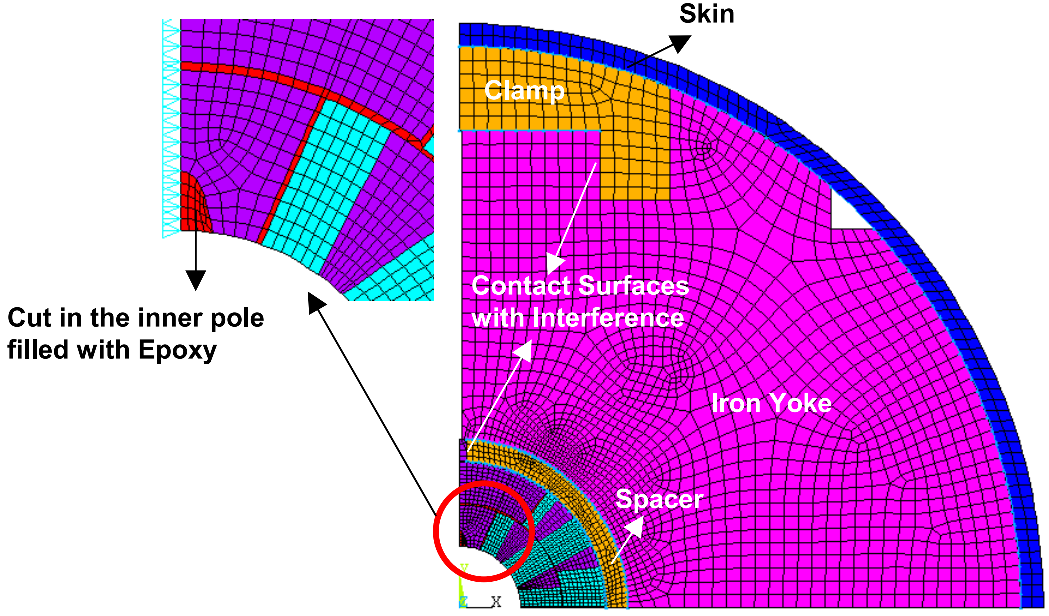


DESIGN FEATURES:

- Wind and React approach
- Ceramic Insulation with Ceramic Binder
- No Interlayer Splice
- Spacers instead of Collars
- The gap between the two iron yoke halves remain open
- Coil prestress provided by both aluminum clamps and Skin

Design Overview: Mechanical Analysis

- **Objective**
  - **To develop a robust mechanical design which is flexible to account for changes in prestress due to manufacturing uncertainties and tolerances**
  - **To optimize the Coil prestress and the stress in the major elements in the coil support structure**



Analysis - Verification

- **Mechanical Model**
  - **A 10 inch long Mechanical model was fabricated and tested to verify the FE Analysis results**

Azimuthal stress, MPa

	Coil Pole	Spacer Mid-Plane	Spacer Pole
Under Press	154 (145)	88 (122)	152 (156)
After Spring back	32 (40)	40 (43)	51 (50)
After Skin Welding	66 (72)	68 (65)	84 (81)
At 77 K	61 (73)	46 (45)	68 (56)

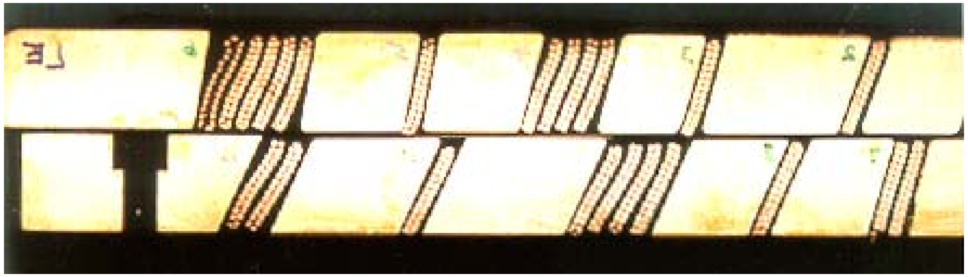
Magnet Technology Overview

- **Fabrication Steps**
  - **End-Part Design and Fabrication**
  - **Cable Insulation**
  - **Coil Winding and Curing**
  - **Coil Reaction**
  - **Splice Joints**
  - **Coil Impregnation**
  - **Yoking and Skinning**

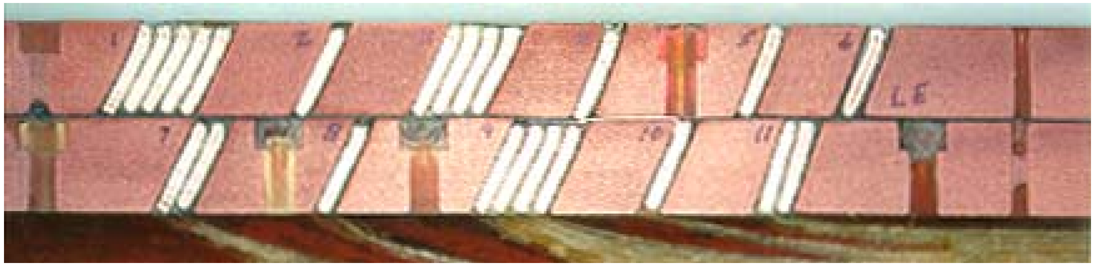
End-Part Design

- The design of End-parts were optimized using the program BEND. Two iterations were performed,

First Generation End-Parts



Second Generation End-Parts



End-Part Fabrication

- **Different manufacturing techniques were investigated to reduce the cost of the fabrication of end-parts**
  - **Laser Sintered parts with quick turn-around time were used to optimize the end-part design**
  - **Five Axis Water Jet Machining was used for manufacturing the end-parts from HFDA-02 magnet onwards.**

Water Jet Machined Part

Manufacturing Technology	Cost for 4 Sets	Cost Per Part*	Machining Time, min
Conventional	32,000	380	60 – 120
Water Jet	14,000	167	10 – 15
Laser Sintered	3,500 (for 1 set)	167	Complete set is done in one pass

* Both conventional and water jet machining involves additional material costs

Cable Insulation

- **S-2 Fiber Glass Tape**
  - **Traditionally being used to insulate Nb_3Sn cable. Involves lot of pre-processing and the final product is very weak to be used with an automated machine to wrap around the cable**
  - **Worked with a weaving company to orient the fibers in the favorable direction and were successful in using S-2 glass tape without any organic binder.**

- **Ceramic Fiber Tape with Ceramic Binder**
  - **Developed by CTD Inc. through SBIR**
  - **The tape does not contain any organic binder and is strong enough to use for wrapping around the cable**
  - **Ceramic Binder is an inorganic adhesive used to form the coils into right shape after winding.**

Cable Insulation Process

- **The in-organic binder is first applied to an already insulated cable by passing through wet rollers. The wet insulated cable is then cured at 80 ^oC for 30 min.**
- **Upon winding, the coil is cured at 150 ^oC for 30 min. and the inorganic binder turns into a bonding agent which provides a rigid shape to the coil**
- **This scheme developed at Fermilab offers the following three advantages -**
  - **Restoration of tape strength after initial binder application**
  - **Possibility of assembling cured coils prior to heat-treatment**
  - **Easiness of cured coil handling**

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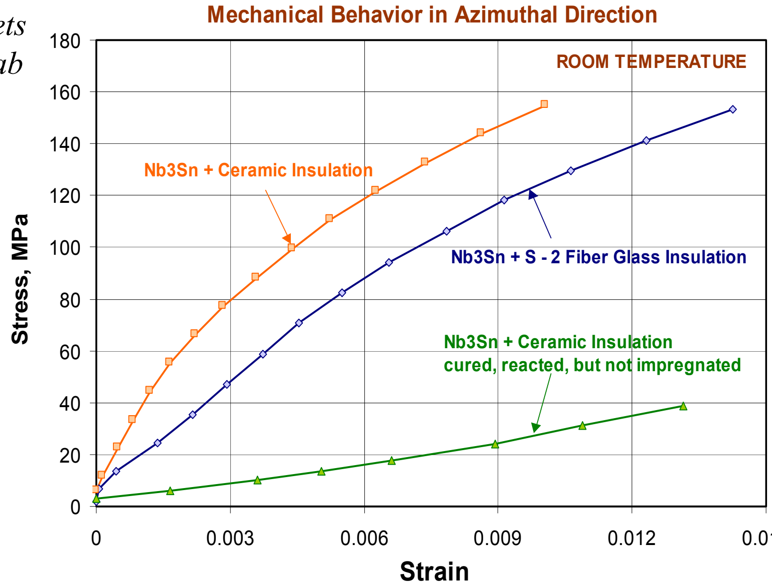
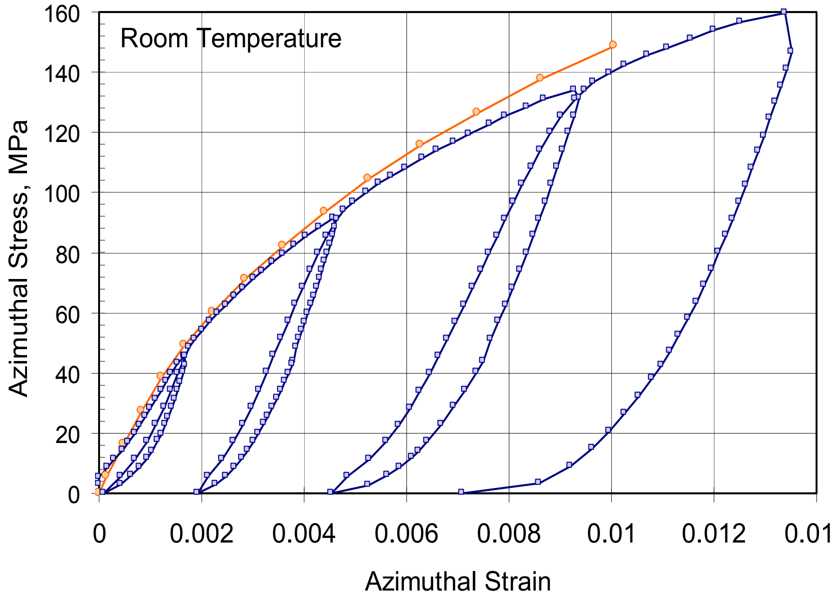
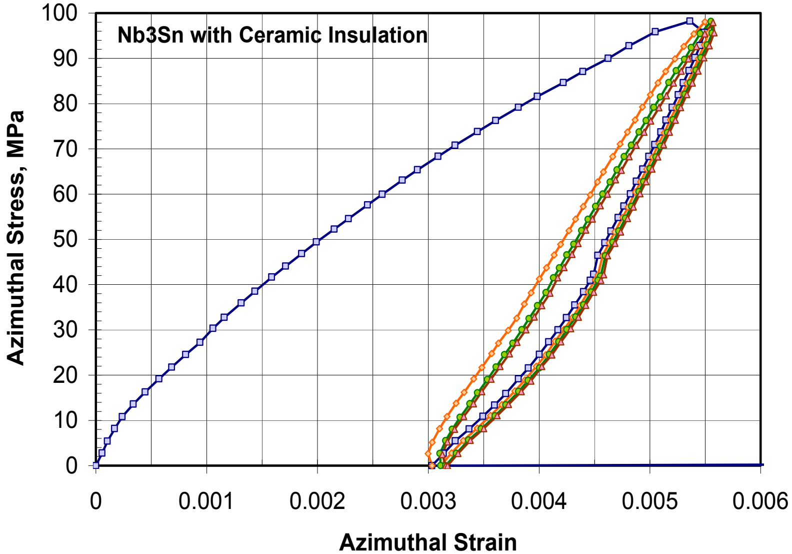
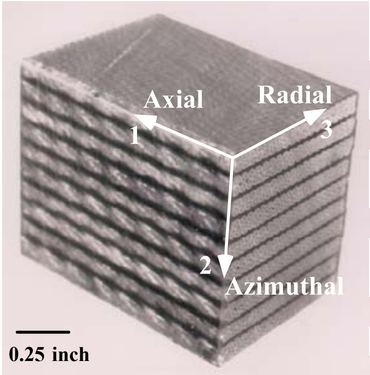
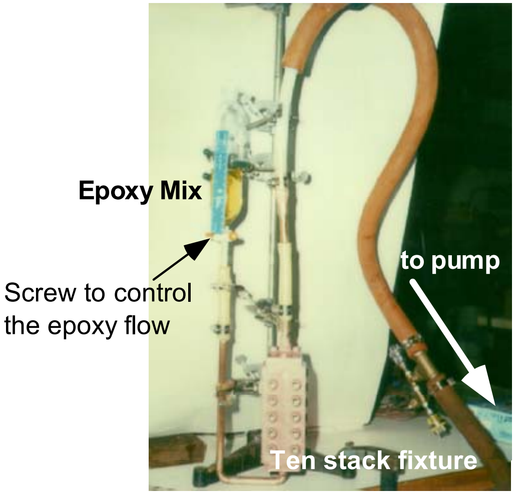
Mechanical Characterization of Impregnated Ten-Stack Samples with Different Insulation Materials





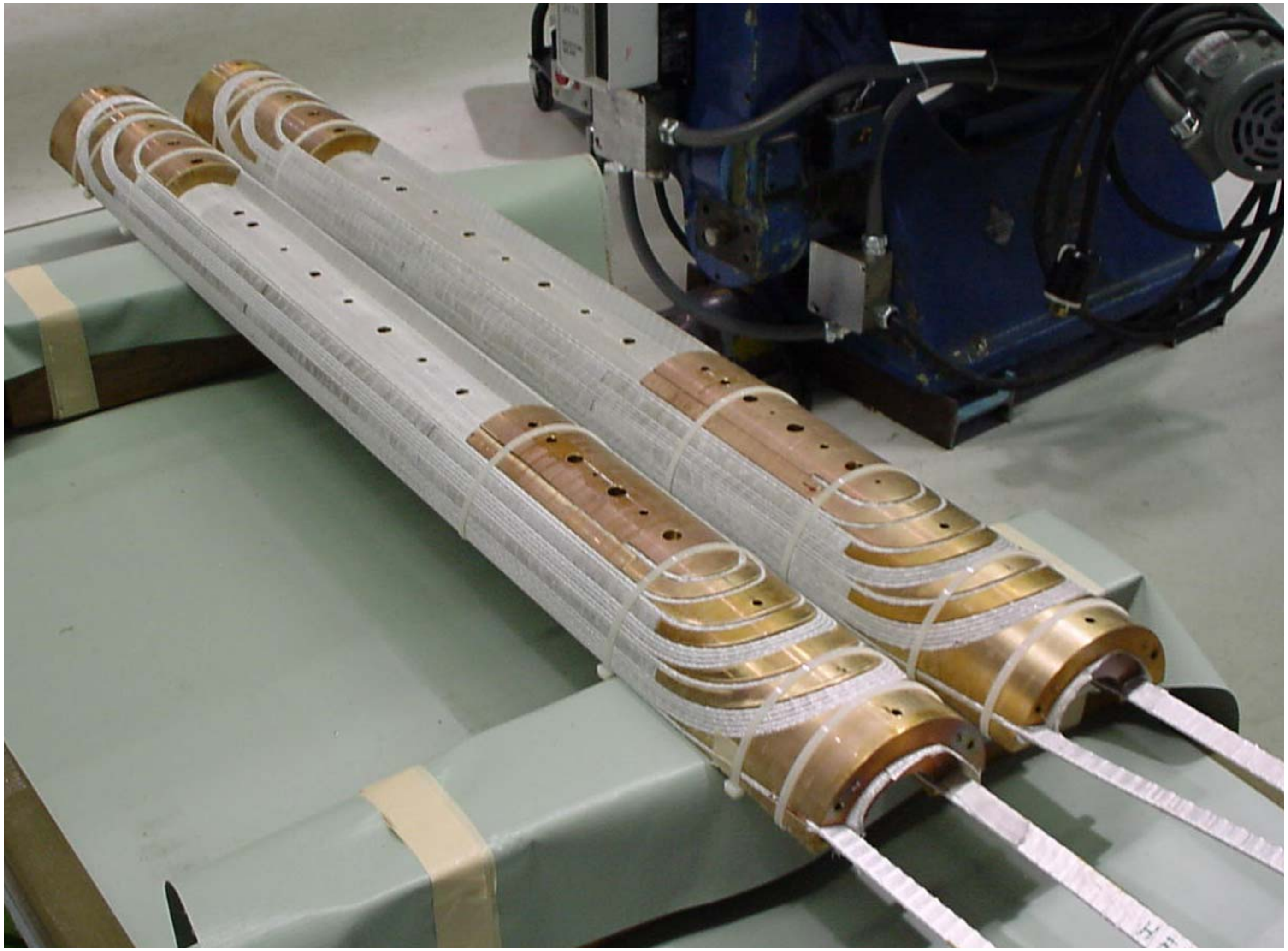




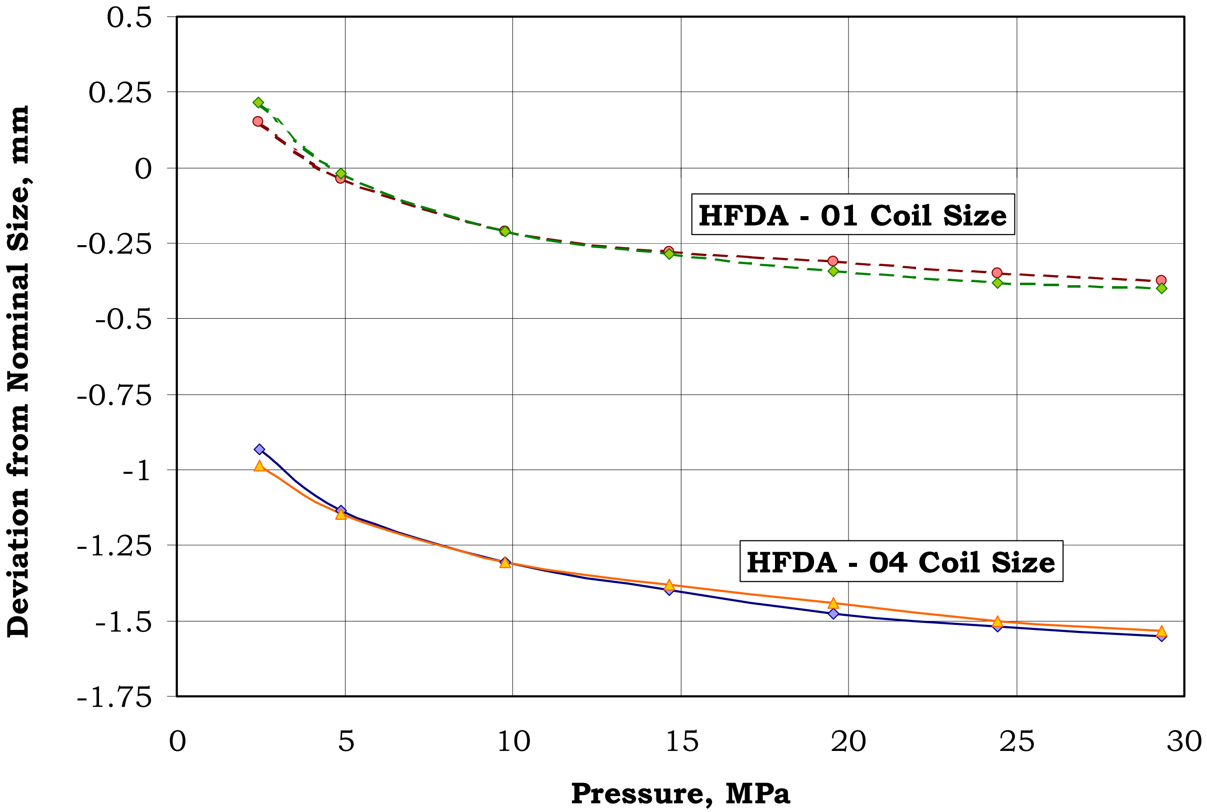


Cured Half Coils

Two half coils ready to be reacted…



Coil Azimuthal Size Measurements



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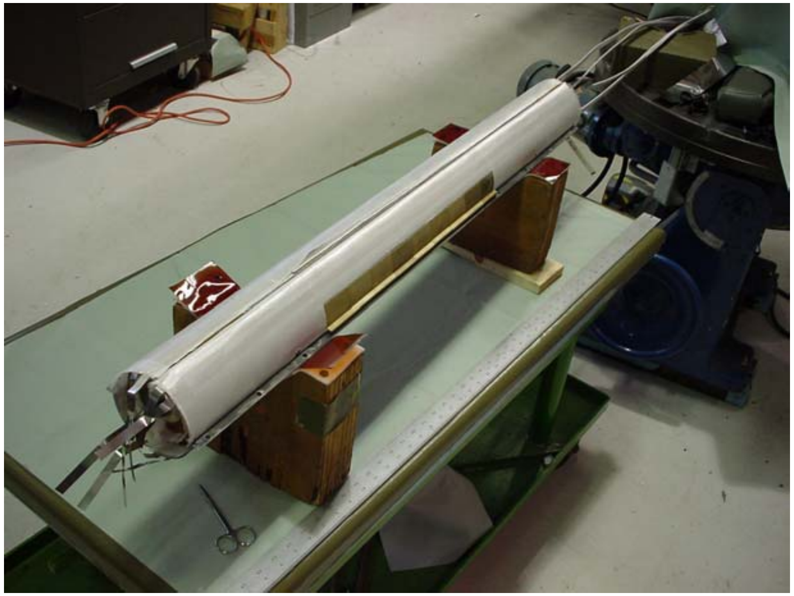
Coil Assembly

Ground Insulation with Quench Protection Heaters

Coils Assembled with Ground Insulation



Coil Reaction

Coils in the Reaction Fixture

Furnace for Heat-treatment

	Ramp Rate ^{o}C/hr	Temperature ^{o}C	Dwell Time hr
Step - 1	25	210	100
Step - 2	50	340	48
Step - 3	75	650	180

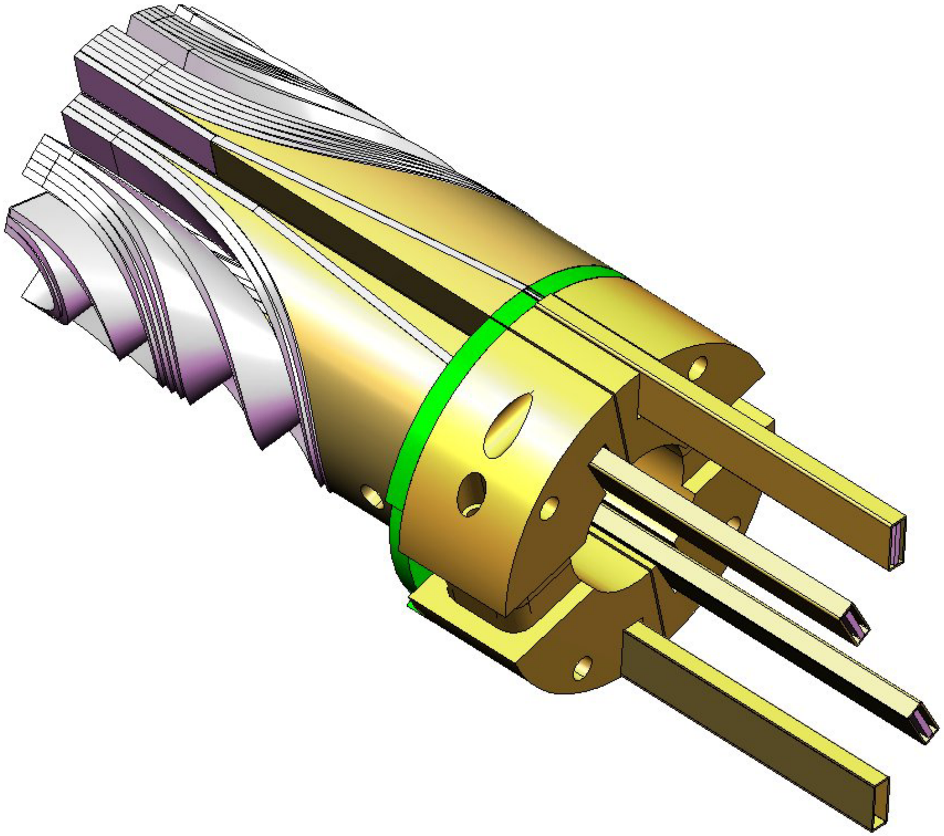
Reacted Coil

- Good bonding between the turns even after reaction

- Easy to handle

Splice Joints

- Each Nb_3Sn lead cable is spliced to two NbTi cables, one on each side



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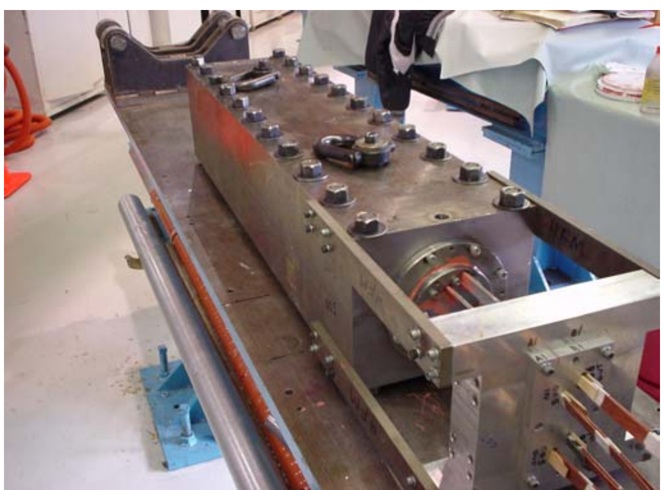
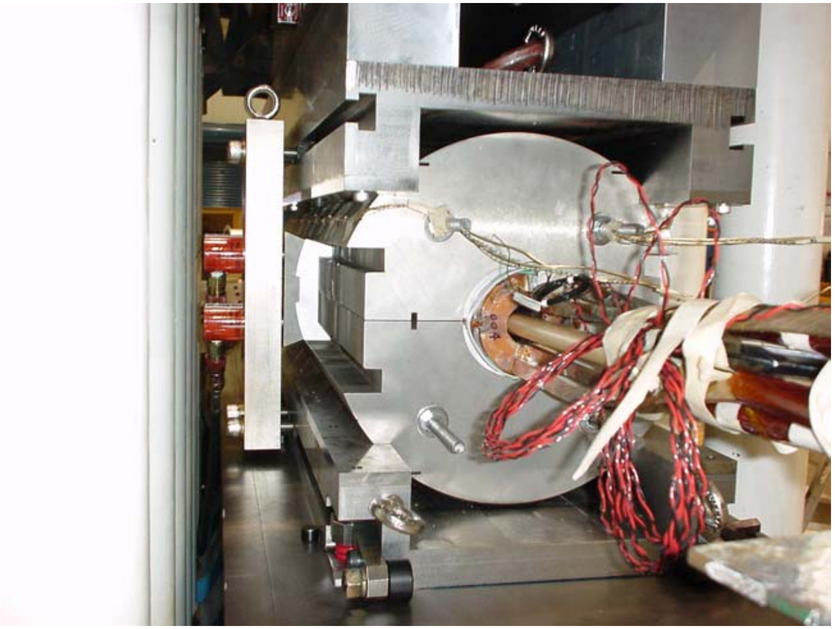
Epoxy Impregnation



Impregnated Coil

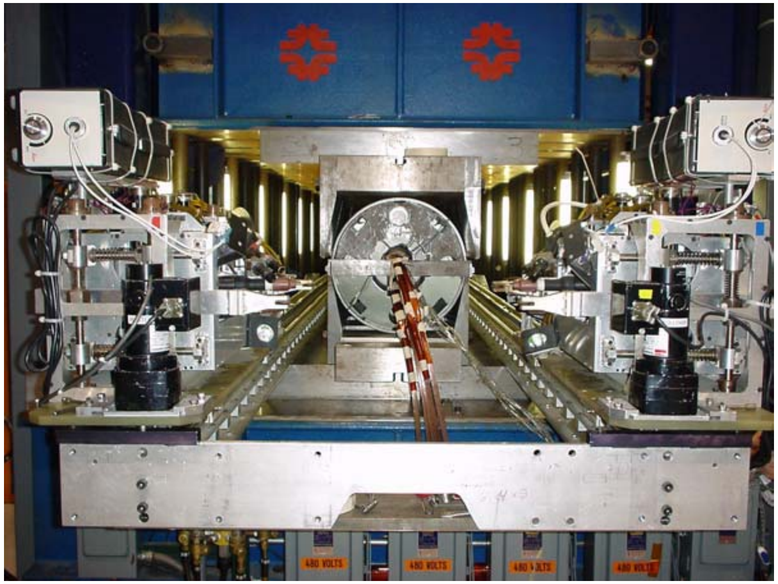
Yoking



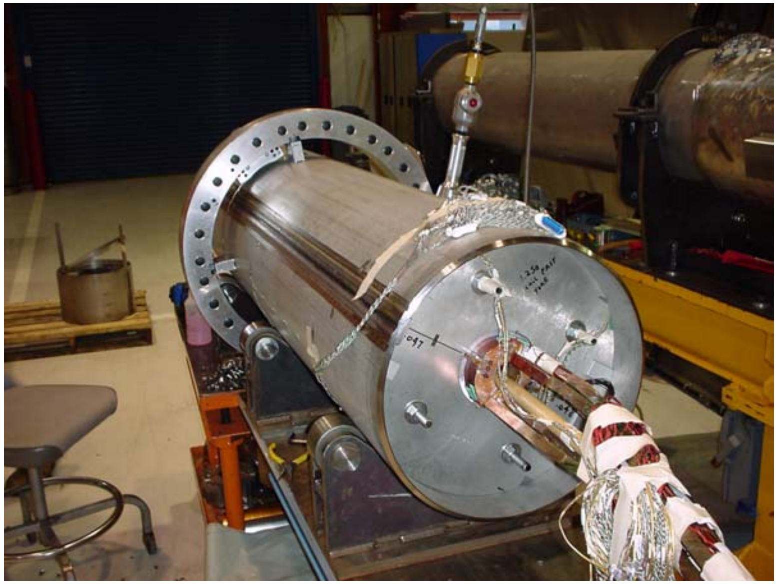
Note: Yoking provides about 30% of the required prestress to the coils

Skinning

Magnet inside the welding press



Magnet after welding skin



Note: Weld Shrinkage provides rest of the pre-stress to the coils

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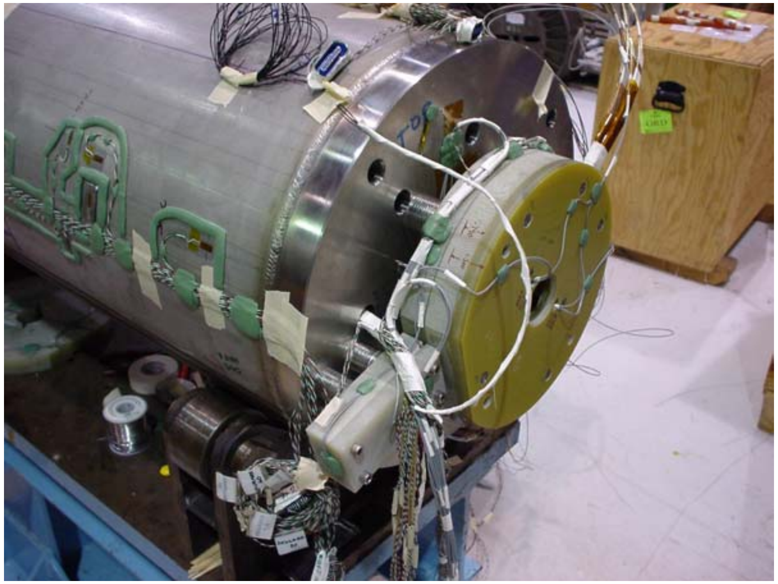
Magnet Final Assembly

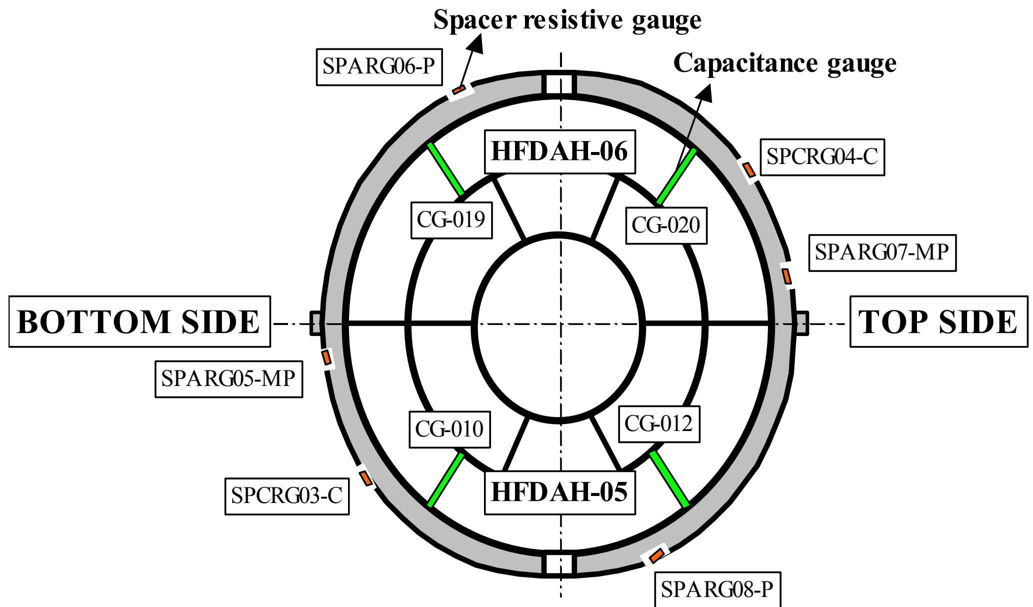


Half Coil splicing assembly

Magnet ready to be tested

Measurements During Magnet Assembly

Instrumentation Layout:



Azimuthal Stress measurements in MPa

	Under Press		During Clamping		After Spring Back		After Welding Skin	
	Coil	Spacer	Coil	Spacer	Coil	Spacer	Coil	Spacer
ANSYS	50	160	--	--	20	108	60	165
HFDA-02	85	213	94	223	30	115	55	159
HFDA-03	76	153	80	157	24	97	54	120

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HFDA-01

- **Magnet fabrication was stopped after coil reaction due to tin-leakage in the conductor**
- **Possible reasons for this behavior –**
  - **Removal of low temperature, 200 °C step from the reaction cycle**
  - **High compaction of coils during reaction due to the formation of the Nb_3Sn Phase.**
  - **The conductor itself was weak to handle the cabling process. Later tests on some of the free cable samples showed tin-leakage**
- **Cable volume expansion during hear-treatment and effect of heat-treatment cycle were investigated**

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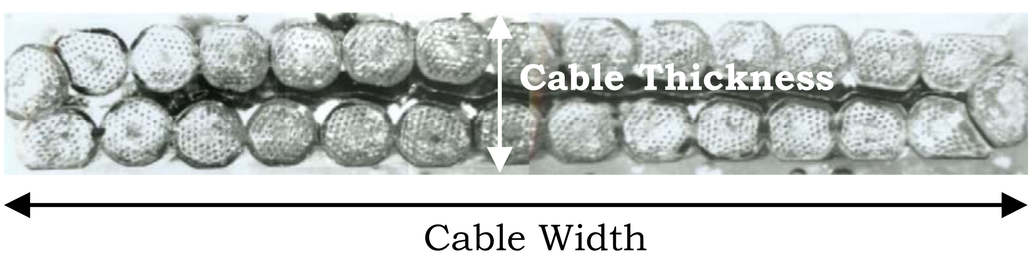
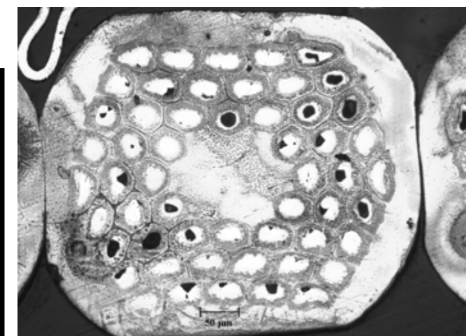
R&D Test Results

❖ Volume expansion of the cable

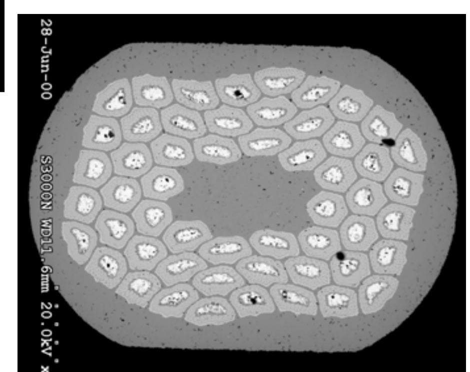
- **Anisotropic volume expansion in the cable compared to isotropic expansion in a virgin strands. Plastic deformation induced during cabling is responsible for the observed behavior**

Manufacturing Technology	Thickness Expansion, μm	Width Expansion, μm
MJR	55	13
PIT	49	12
IT	85	--
ITER	25	4





Strand in a Rutherford cable



Compressed strand

Changes Introduced Based on HFDA-01

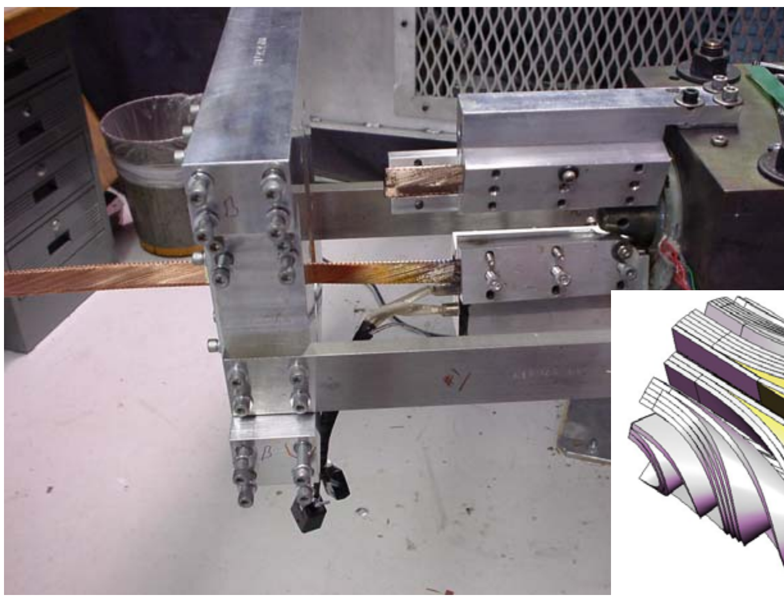
- The azimuthal coil size after curing was optimized such that the coil is at the nominal size after reaction. This will eliminate the excessive pressure on the conductor during reaction
    - The coil azimuthal size before reaction was reduced by about 1.0 mm by decreasing the amount of overlap of the insulation tape from 50% to 40%

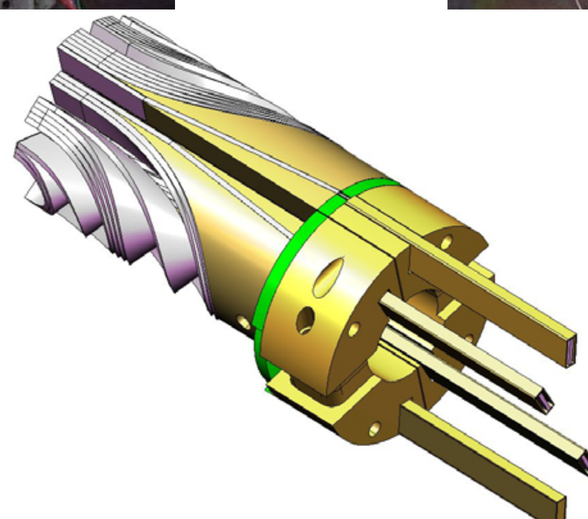
- The reaction cycle was modified to have a low temperature step in the beginning to allow tin to diffuse in solid phase.
    - Several cable samples were reacted using various heat-treatment cycles to study the issue of tin-leakage

HFDA-02

- The outer layer lead cable was broken during the splicing operation. It was repaired by moving the splice joint into the end-saddle area.

Repaired Splice Joint





Splice Tooling

Finished splice Joints

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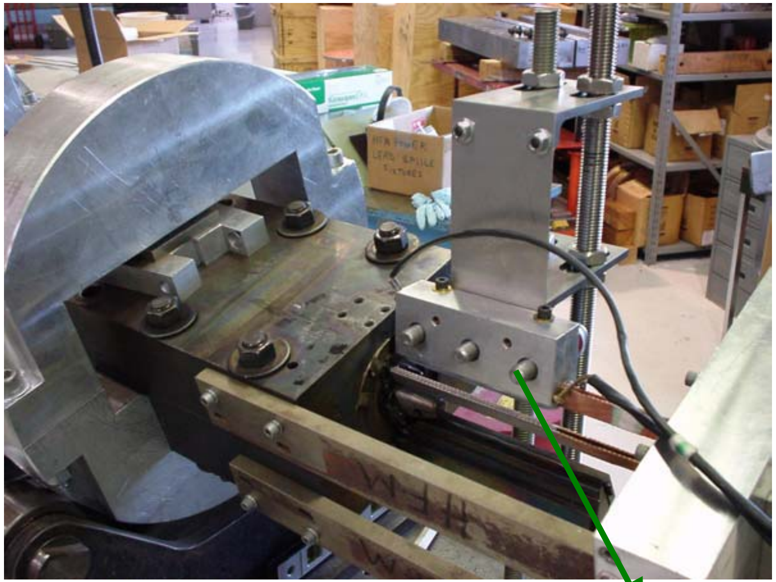
Changes Introduced in Splice Tooling

- **Each Nb_3Sn lead was spliced individually to avoid damage due to misalignment during assembly**
- **The tooling was made flexible to account for any motion during the heating process**



HFDA-03 Splice Joints

Spring loaded

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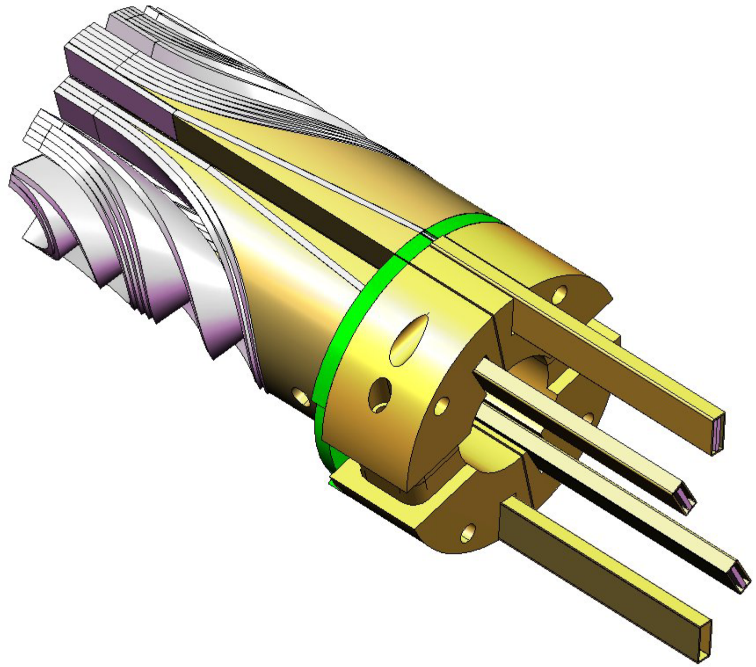
HFDA-03

- **The fabrication of HFDA-03 went smoothly without any set-backs. However both HFDA-02 and HFDA-03 had very similar quench performance**
  - **Based on the voltage tap data, it was concluded that the quench location was close to the splice joint in both the magnets (Zlobin will cover this in the next presentation)**



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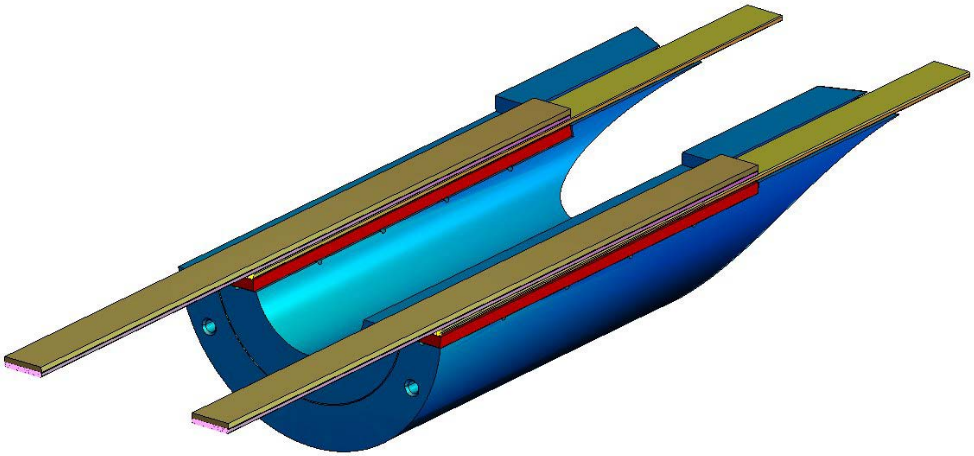
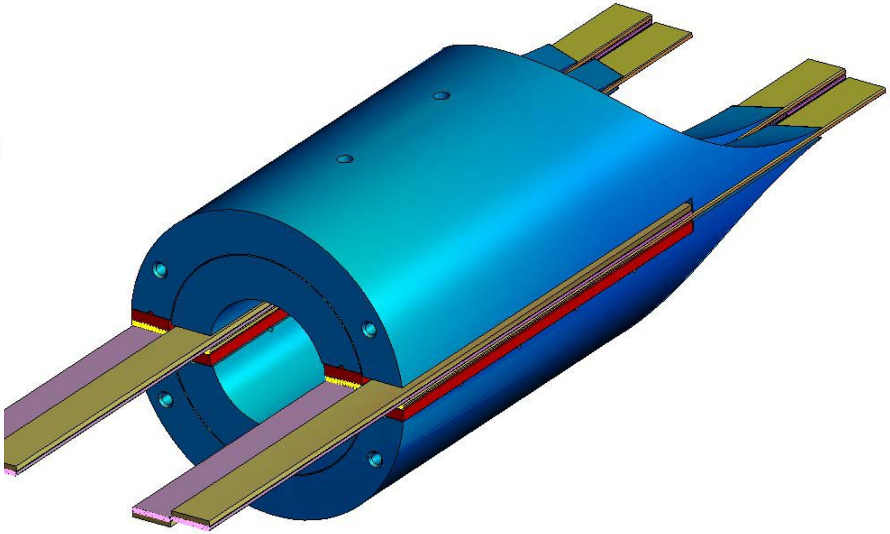
Changes Introduced Based on HFDA-03

- **Design changes for Splice Joints**





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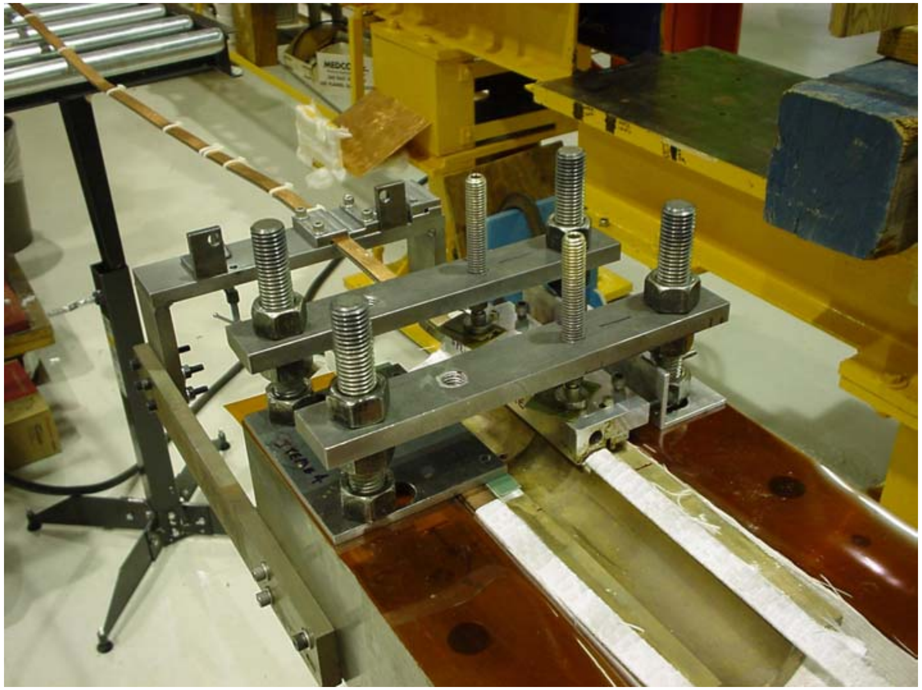
Changes Introduced Based on HFDA-03

- **Splicing Procedure**
  - **Each half coil will be spliced separately.**



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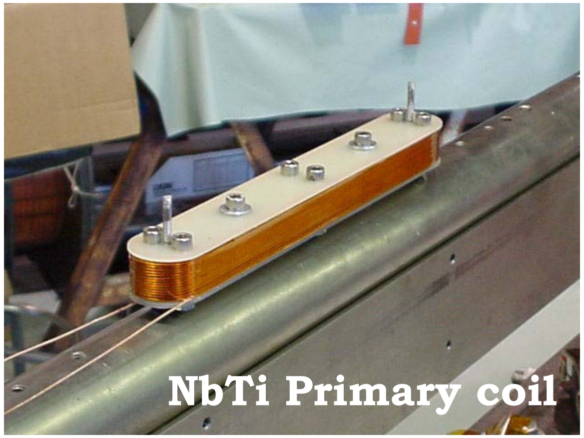
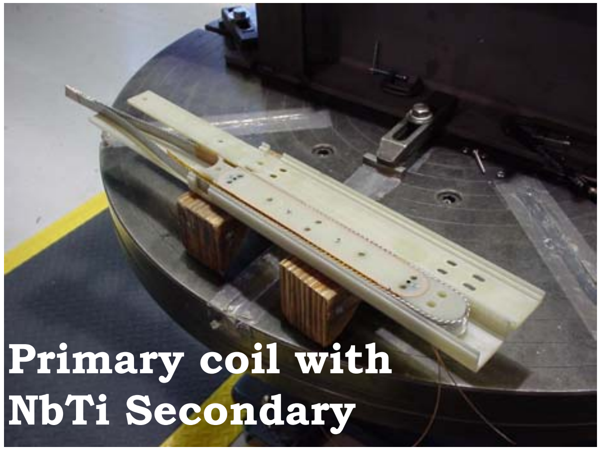
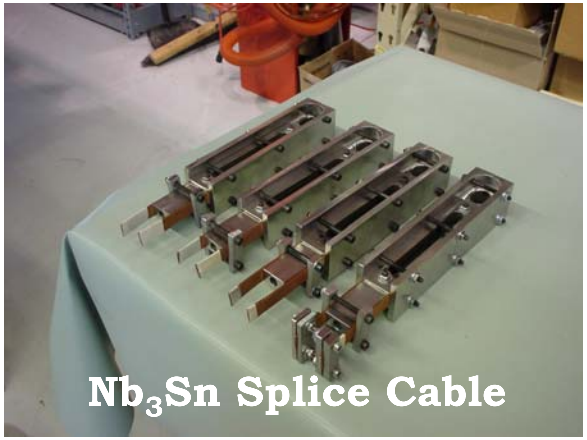
Verification

❖ **Splice Testing: Transformer Design & Fabrication**







Verification

❖ Splice Test Results:

Sample #	Splice Resistance nano-ohms	Current kA	Comments
1	6 (1 + 5)	13	Quenched. The reason is the mechanical strain induced in Nb_3Sn cable due to relaxation of NbTi cable.
2	2.5 (1.5 + 1)	16	Quenched. The cable might have been displaced during splicing. Acceptable splice resistance
3	5 (2 + 3)	19	No quench. Splice Tooling was modified. However, low pressure was applied during splicing operation which resulted in high splice resistance.
4	2.5	22.5	No quench. Good quality of splices with acceptable splice resistance. Pressure during splicing operation was increased.

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Verification

❖ Splice Test Results:

Effect of Pressure

Pressure MPa	Splice Thickness Deviation mm	Splice Resistance nano-ohms	Current* kA
2	0.625	2.2	16.5
5	0.500	1.7	18.6
9	0.375	1.4	20.5
23	0.250	1.2	21.5
38	N/A	1.1	21.8

Effect of conductor displacement

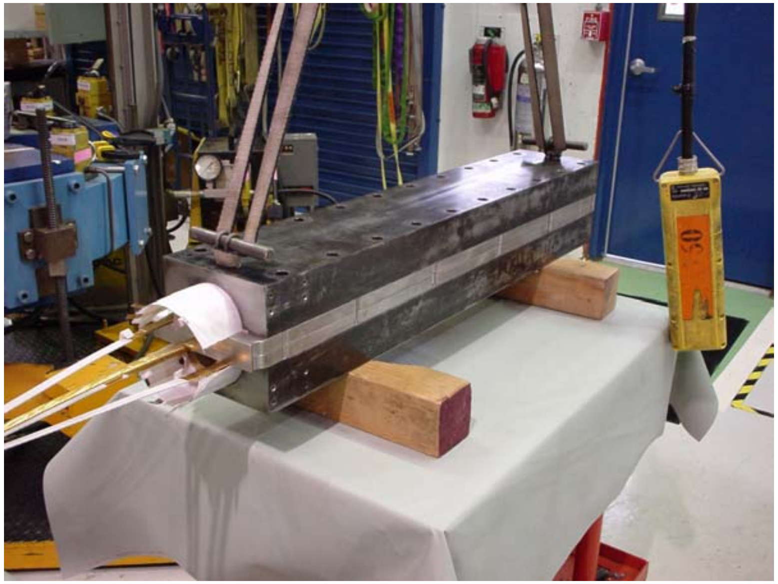
Splice Tip Displacement, mm	Displacement @ 7 mm from Clamp, mm	Current* kA	Splice Resistance nano-ohms
17 (out of cable plane)	0.250	19.5	1.6
4 (in the cable plane)	0.200	17.6	2.1

***No quenches were observed**

Current Magnet: HFDA-04

❖ Reaction Fixture

- **In order to control the coil mid-plane and to have the option of splicing each half-coil separately, the reaction fixture was modified**
  - Each half coil was fixed to one half of the reaction fixture using mid-plane spacers.



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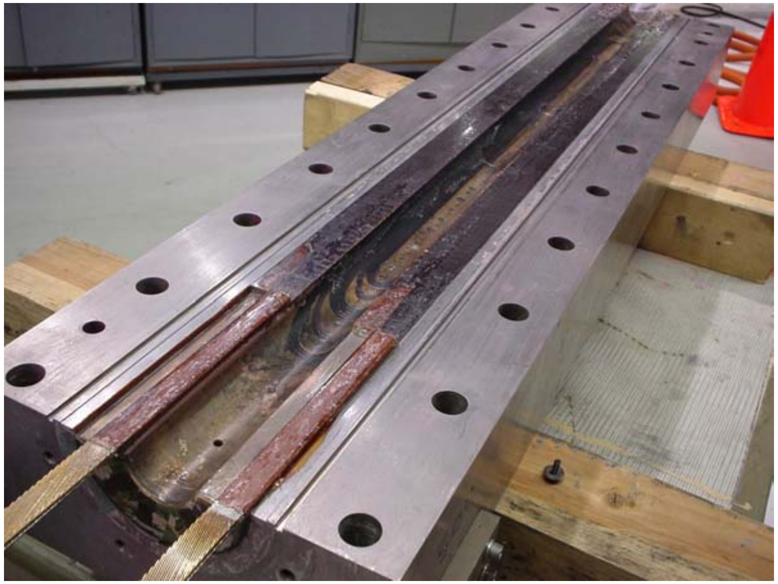
HFDA-04

❖ First Half Coil: Splice Joints and Impregnation

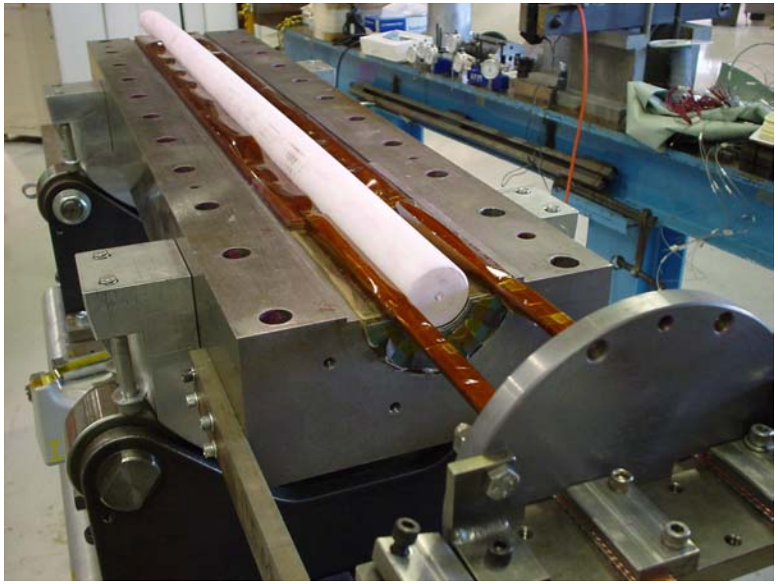
Splice Joints before Impregnation



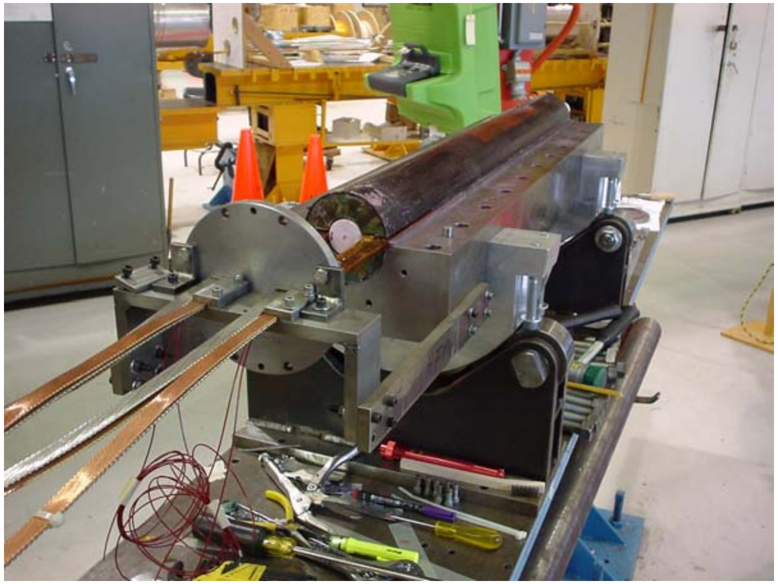
Half Coil 07 after Impregnation

HFDA-04

❖ Second Half Coil: Splicing and Impregnation



Splice Joints before Impregnation

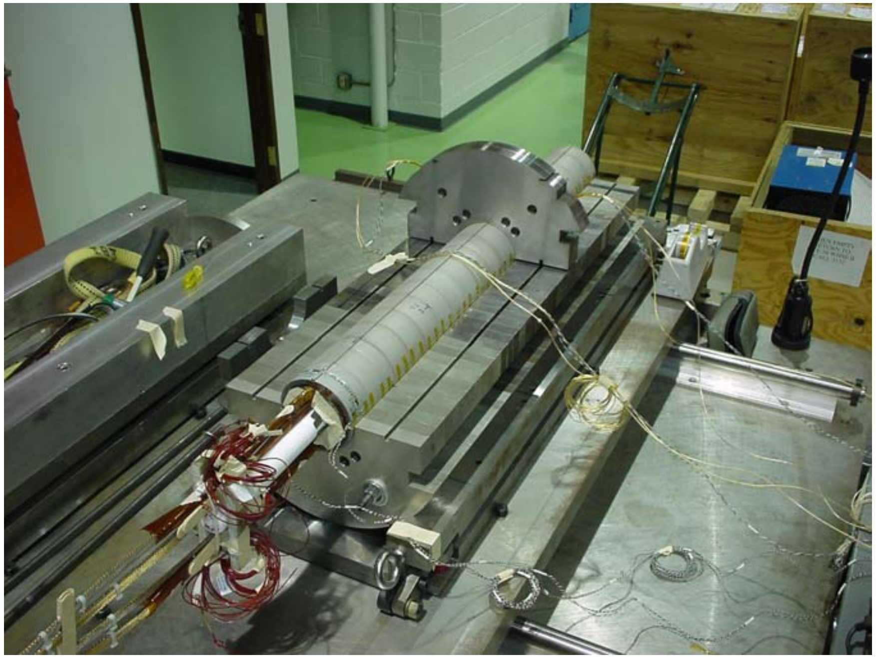


Second half coil was impregnated along with the first half coil which has already been impregnated once.

HFDA-04

- Coil impregnation is completed and the magnet is currently being yoked.

Impregnated Coil Assembly



Coil Assembly with Spacers and Yoke Laminations

Typical Magnet Schedule

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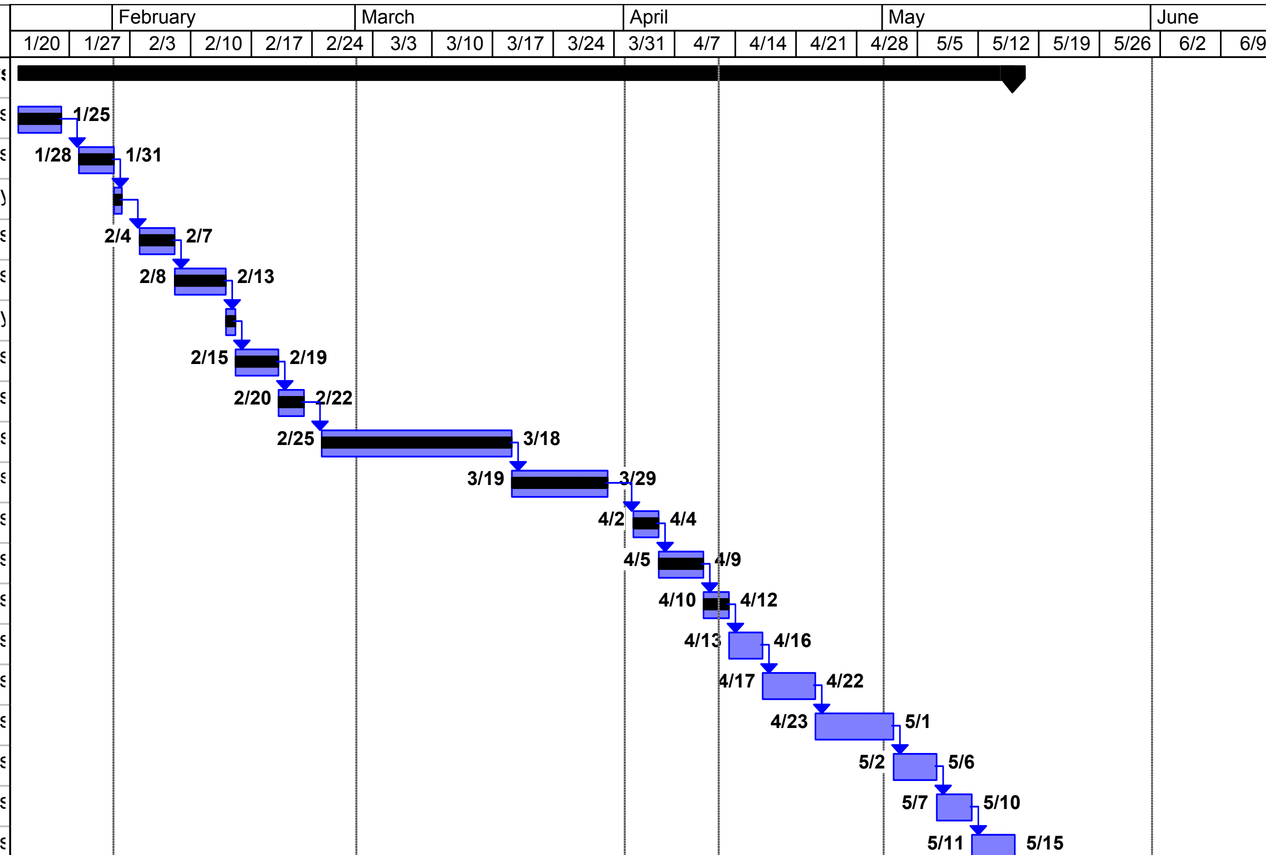
- It takes us about four and half months to built a short model.

ID		Task Name	Duration
2		**HFDA-04 Fabrication**	**88 days**
3	✓	Inner Coil 07 Winding & Curing	5 days
4	✓	Outer Coil 07 Winding & Curing	4 days
5	✓	Splice Samples Preperation	1 day
6	✓	Inner Coil 08 Winding & Curing	4 days
7	✓	Outer Coil 08 Winding & Curing	4 days
8	✓	Half Coil Measurements	1 day
9	✓	Ground Insulation	3 days
10	✓	Coil Assembly for Reaction	3 days
11	✓	Coil Reaction	16 days
12	✓	Tooling Delay / Splice Practice	9 days
13	✓	Half Coil - A Splicing / Assembly	3 days
14	✓	Half Coil - A Impregnation	3 days
15	✓	Half Coil - B Splicing / Assembly	3 days
16		Half Coil - B Impregnation	3 days
17		Coil Assembly & Instrumentation	5 days
18		Yoking & Skinning	8 days
19		End-Plate Installation	4 days
20		Final Assembly	4 days
21		Hypertronics	4 days



Summary / Status

- Splice Joints have been re-designed to support the Nb_3Sn cable
- A transformer has been designed, fabricated and used to test the splice joints in the same configuration as will be used in the current magnet
- HFDA-04 is under production. The coils have been impregnated and ready to be yoked. Expected to complete the fabrication by May 15th
- HFDA-05 production will begin in June depending upon the test results of HFDA-04
- Start fabrication of the mechanical model of 2-in-1 Warm Iron Yoke Design

Cos-theta dipole test results

Outlines:

HFDA02,03 design summary

Instrumentation

Test plan

Quench performance

Magnetic measurements

Quench heater studies

A. Zlobin

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Model design and fabrication features

Three short models of Nb_3Sn cos-theta dipole have been fabricated during 2000-2001 and last two have been tested in 2001.

	HFDA02/HFDA03
Strand	Nb3Sn MJR (OST), D=1.0 mm, deff=115 µm, Cu:nonCu=0.92
Cable	N=28, 25 µm SS core, PF=0.88, keystone
Insulation	125 µm ceramic tape with 30-40% overlap + ceramic binder
Coil curing	150C/0.5h
Coil reaction	Three step cycle: 210C/100h+340C/48h+650C/180h
Coil impregnation	Epoxy
Azimuthal outer coil pre-stress	55 MPa
Longitudinal pre-load	500 lbs per bullet
Ic	20.08 kA
Bmax	11 T

These are two practically identical magnets

Specific features of HFDA-02

- The coil size after curing was optimized such that after reaction the coils will be at the nominal size in order to eliminate Sn leaks during reaction.
- One half-coil was about 0.2 mm larger than the other due to difference in mid-thickness of the bare cable used.
- The reaction cycle was modified to have a low temperature step in the beginning to allow tin to diffuse in solid phase. This low temperature step was added to avoid tin-leakage.
- The coil end-parts were optimized for better conductor support. The end-parts were manufactured using water-jet machining which is more cost effective compared to conventional 5-axis CNC machining.
- Ground Insulation was modified from three layers of 0.125 mm thick ceramic cloth to two layers of 0.25 mm thick ceramic cloth.
- Quench protection heaters were installed between the two 0.25 mm thick layers of ground insulation.

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Specific features of HFDA-03

- The two half-coils of HFDA-03 have almost the same azimuthal size.
- Ground Insulation consisted of three layers of 0.125 mm thick ceramic cloth with the strip heaters weaved into the middle layer.
- New splice tooling was designed and procured for this magnet. Each Nb3Sn lead was spliced independently of the other and this enabled greater flexibility in adjusting the tooling. Further copper boxes were not used for the splice joints.
- The half-coil splice assembly was achieved without fixing the leads using “green putty” to the G-10 spacers. This would enable the leads to move under Lorentz forces if necessary.
- Iron yoke design was optimized for this magnet taking into account the saturation effects.
- The stainless steel laminations were extended to cover part of the splice support block. This is to push the discontinuity in stress away from the Nb3Sn lead.

Instrumentation

- Internal instrumentation
  - Stress/strain gauges
  - Voltage taps
  - Temperature gauges

- External instrumentation
  - Rotating coils
  - Thermometers
  - Pressure gauges
  - Quench antenna

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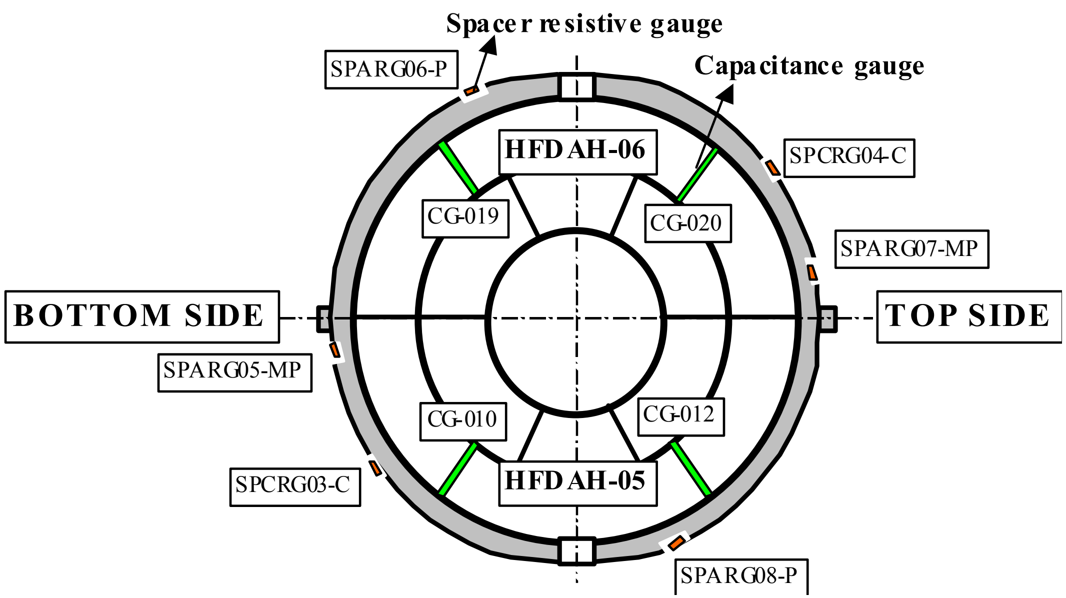
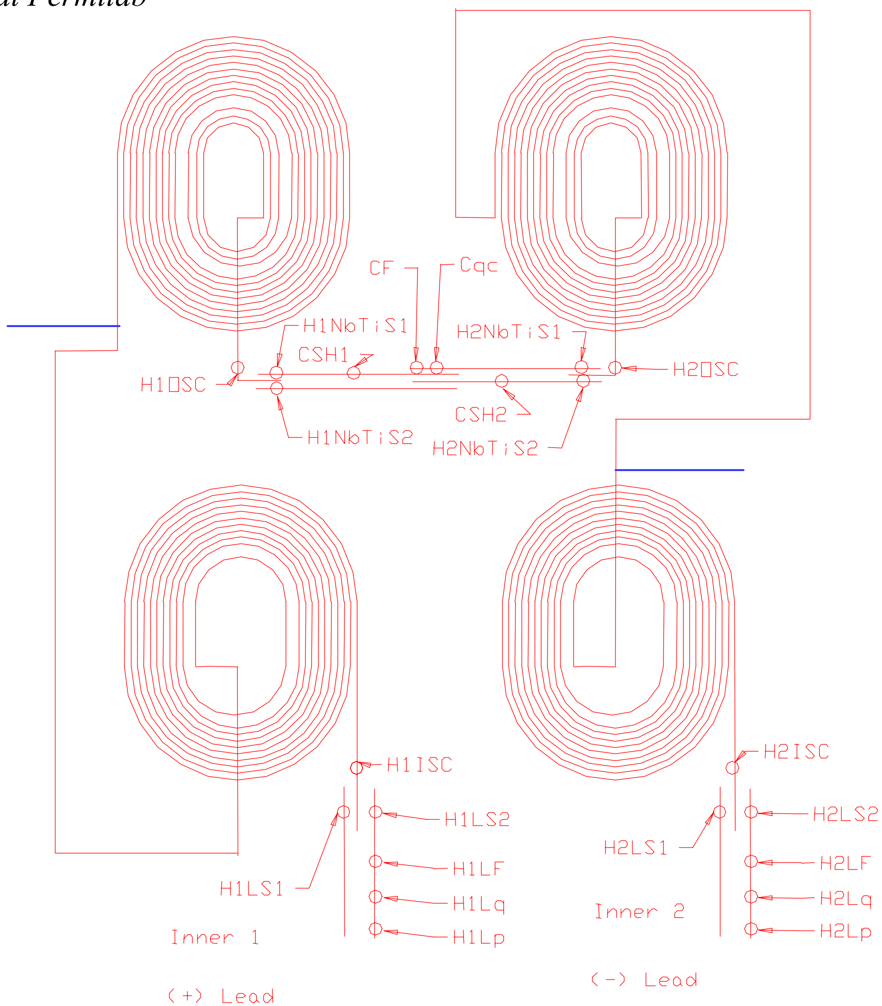
Stress/strain gauges

- 4 cap gauges on the outer coils
- 6 resistive gauges on the Al spacers and 4 on the skin
- 4 bullet gauges on lead and 4 on return end



Voltage taps



- To minimize risk associated with VT installation the number of VTs was reduced to the minimum
- Voltage Tap Schematic
  - HFDA02 (red): each half-coil and splices
  - HFDA03 (red + blue): each layer of half-coils and splices

Test plan

- Production tests
  - Mechanical measurements
  - Electrical measurements
  - Magnetic measurement
- Performance tests
  - Mechanical performance
  - Quench performance
  - Field quality
  - AC losses
  - Quench protection
  - Reproducibility

Vertical Magnet Test Facility

- Cold tests were performed in VMTF dewar.
- VMTF Parameters:
  - Toper =1.8 - 4.5 K
  - Ioper = 0-18 kA
  - Magnet length - up to 4 m
  - He volume - 800 liters
  - New 40-mm warm finger
- HFDA02 was tested in two thermal cycles without and with passive corrector.
- HFDA03 was tested in one thermal cycle.

Magnet training

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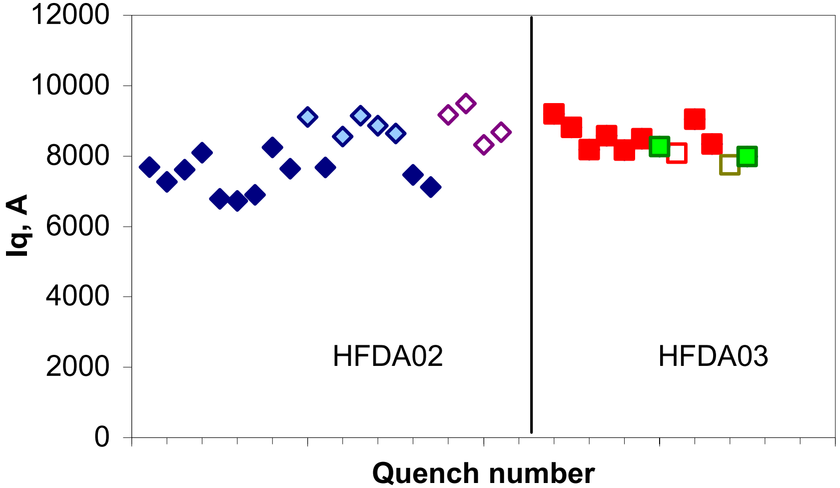

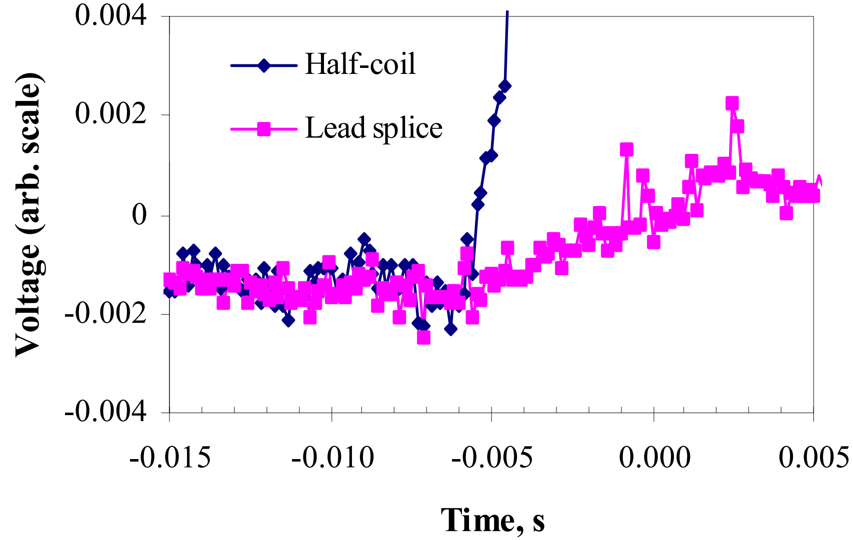

✓All quenches in both magnets occurred in the Nb_3Sn coil leads just near their splices with the NbTi cables. It is confirmed by the signals from the voltage taps installed on the coils and in the splice regions.

✓The quenches never occurred in the magnet coils.

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Quench performance

✓ The quenches were not caused by splice DC or AC heating:

- Splice resistance measurements

Splice Segment	Resistance ($n\Omega$)	Error ($n\Omega$)	Range (A)
02	0.22	0.08	3000-6000
03	1.07	0.03	1000-7000
10	0.48	0.03	1000-7000
11	0.91	0.07	3000-7000

- Tests at different current ramp rates (5-500 A/s)
- Tests with single NbTi leads

Conclusion: the observed quench performance is due to the Ic degradation of Nb_3Sn cable in the splice region during coil reaction or cable mechanical damage during splicing and magnet assembly.

Geometrical harmonics

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GEOMETRICAL HARMONICS IN MAGNET BODY (I=3000A)

	Design values		HFDA02		HFDA03	
n	$\sigma_{an,bn}$	b_n	a_n	b_n	a_n	b_n
2	1.20	-	-9.6	4.1	1.93	-7.13
3	0.56	0.00	-0.2	-4.0	0.81	-2.36
4	0.28	-	-1.1	0.4	-0.75	-0.19
5	0.10	0.00	0.3	0.0	0.04	-0.53
6	0.05	-	0.3	0.0	0.03	0.12
7	0.02	0.00	-0.1	0.1	0.03	0.04
8*	0.01	-	-	-	-	-
9	0.00	-0.09	-0.2	-0.2	0.04	-0.01

*The measured a_8/b_8 data were used for the centering correction.

- ✓First time field quality was measured in two similar Nb3Sn magnets.
- ✓A noticeable improvement of field quality in HFDA03 with respect to HFDA02 due to better shimming of HFDA03 coil .
- ✓Some large b2, b3, a4 and b5 which exceed 3 sigma of expected RMS field errors due to 50 ⌈m coil block displacements are still present.

Coil cross-section study

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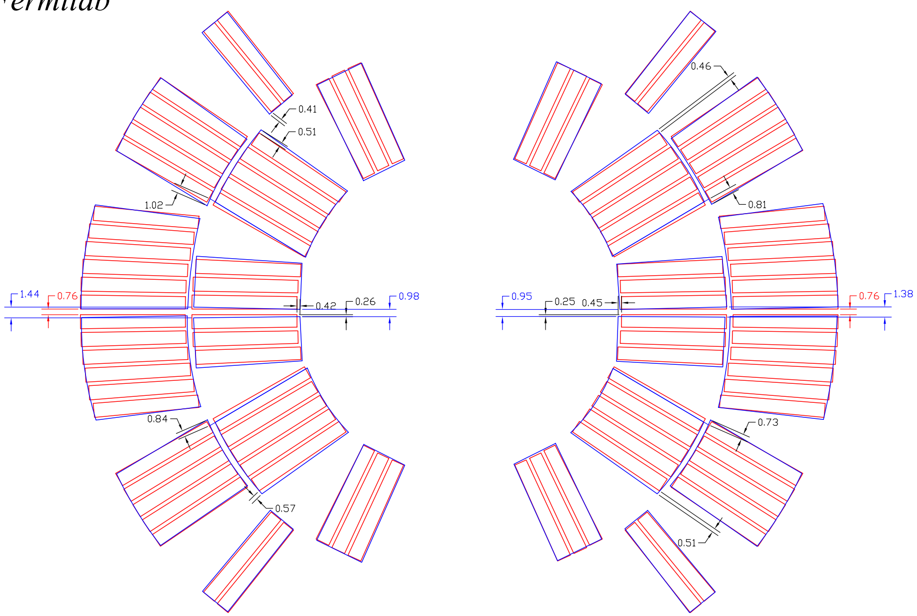

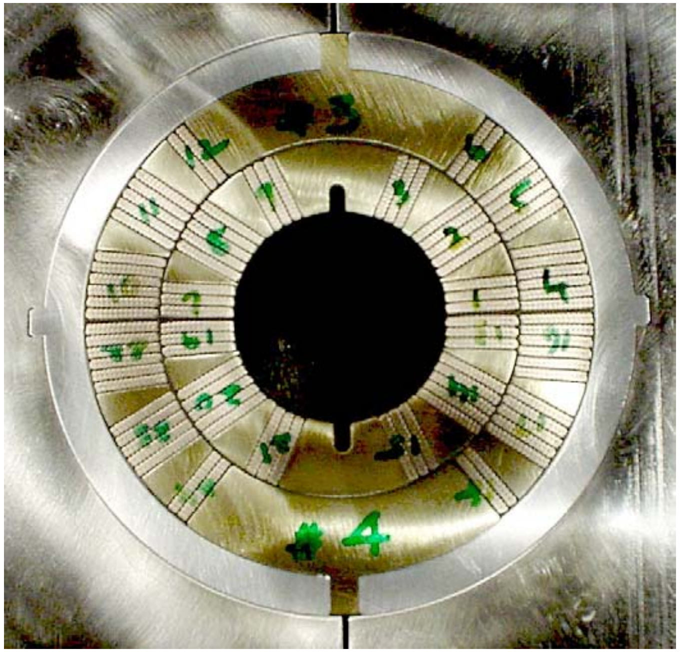

- Cross-section of HFDA02 was measured and compared with the design one
- Large block displacements were observed
- Wedge accuracy – Quality Control
- Asymmetry and shift of coil mid-planes during reaction. Optimizing the reaction and impregnation tooling and procedures will reduce this effect.

Coil magnetization effect

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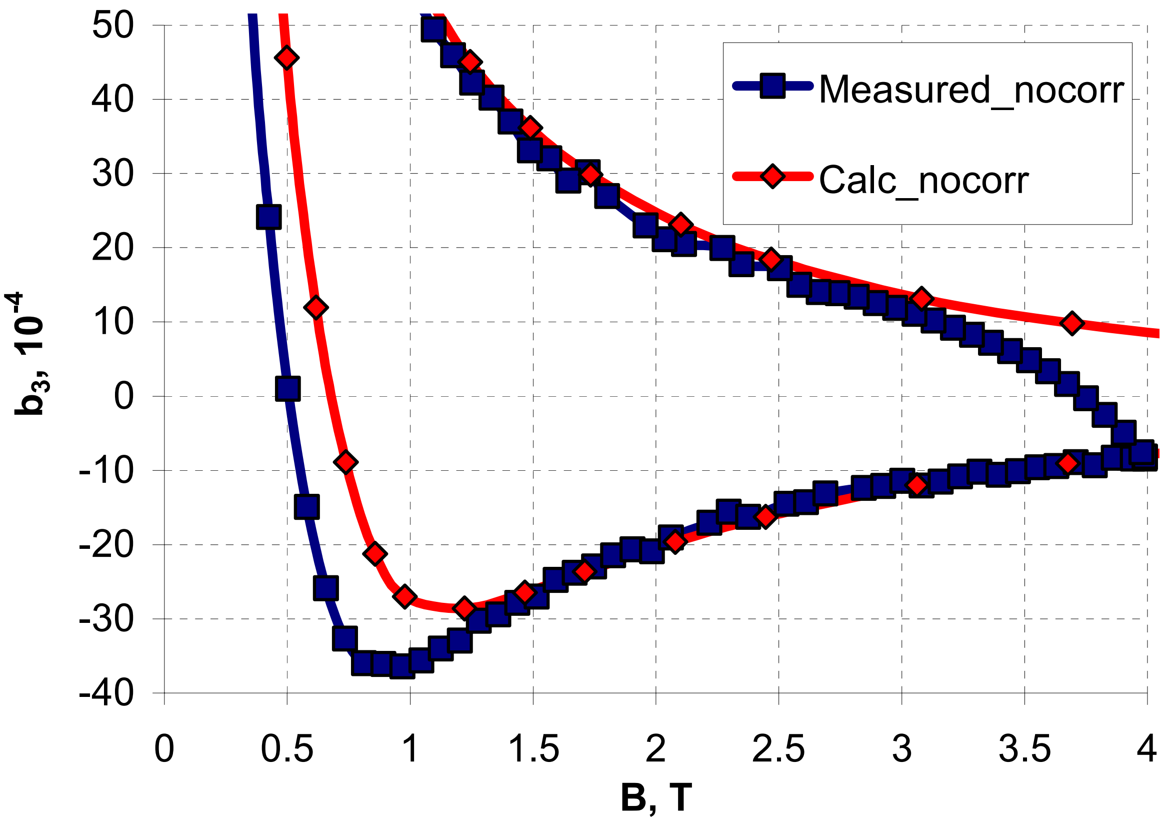

- ✓Model for the analysis of coil magnetization effect based on the OPERA code has been developed
- ✓Model uses experimental data for Nb3Sn strands magnetization measured at Fermilab
- ✓Magnetization harmonics calculations reproduce the measured values over a wide range of currents.
- ✓The width of the b3 hysteresis loop is large ~50 units at 1 kA due to high Jc and large d_{eff}~100 μm in MJR Nb_3Sn strands.

Passive corrector tests

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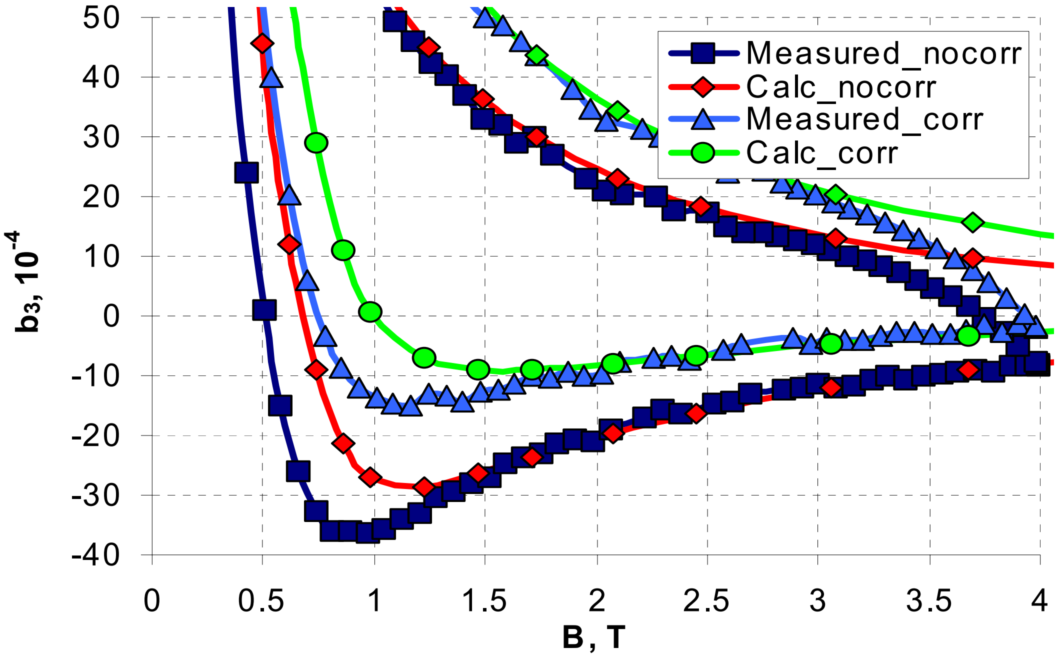
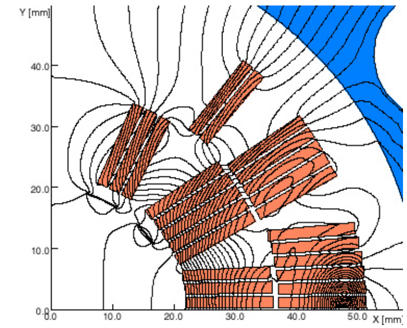


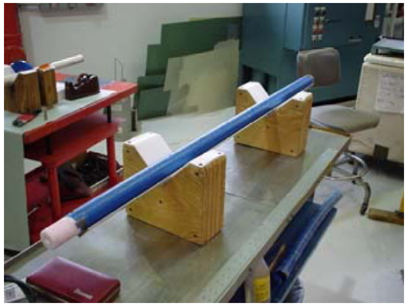
PASSIVE CORRECTOR EFFICIENCY.

	Before correction		After correction		Correction factor	
	calc	meas	calc	meas	calc	meas
$b_3(4T) - b_3(1.5T)$	16.9	15.8	6.6	7.9	2.6	2.0
$b_5(4T) - b_5(1.5T)$	2.36	2.36	1.36	1.36	1.7	1.7



Three passive corrector models have been fabricated:

✓ Corrector model #1 has been tested with HFDA03



✓Corrector model #2 will be tested with HFDA03 next week

✓Corrector model #3 will be tested with HFDA04 in May 2002

Harmonics decay and “snapback”

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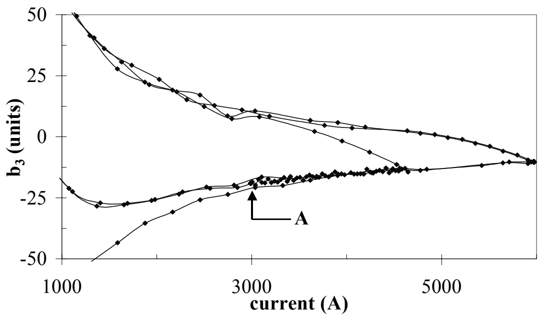
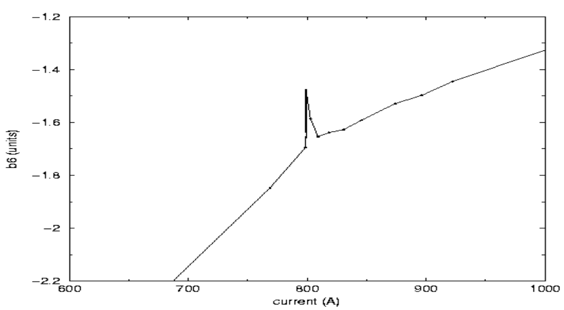
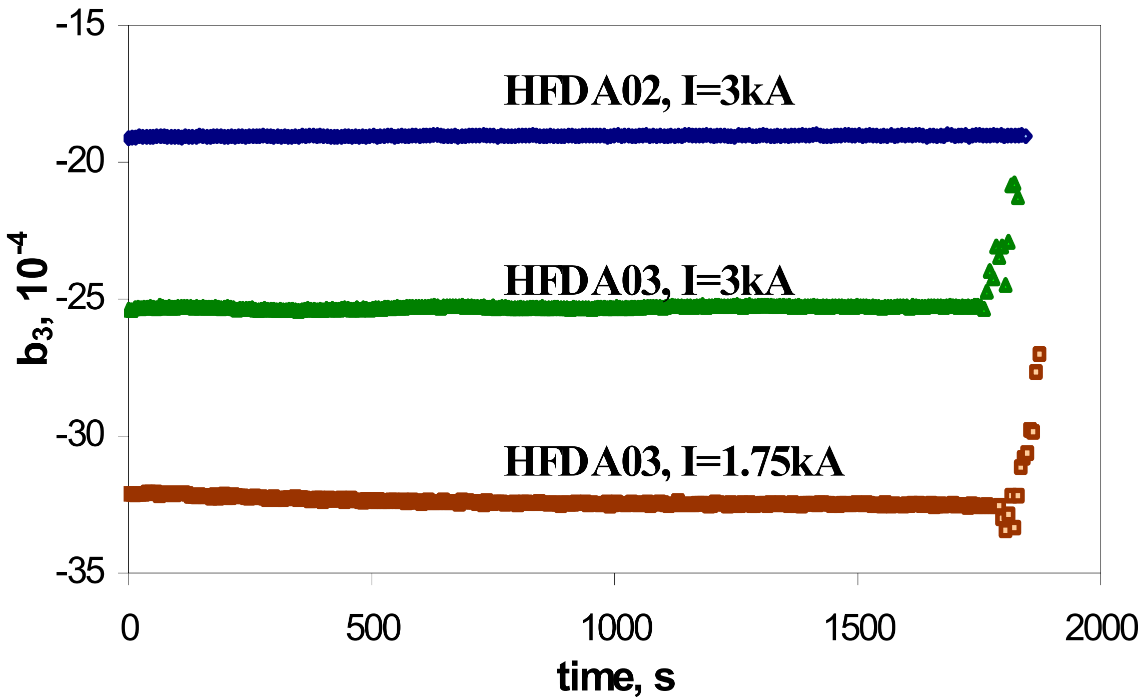


HGQ05





- ✓First time “snap-back” effect was studied in Nb3Sn accelerator magnet.
- ✓Measurements were performed during injection plateau at 3 and 1.75 kA.
- ✓The plateau was preceded by two cycles: 0-6500-0 A at dI/dt=40 A/s.
- ✓Changes in b3 and b5 are very small (<2%) with respect to those observed in NbTi accelerator magnets (HGQ~20%).

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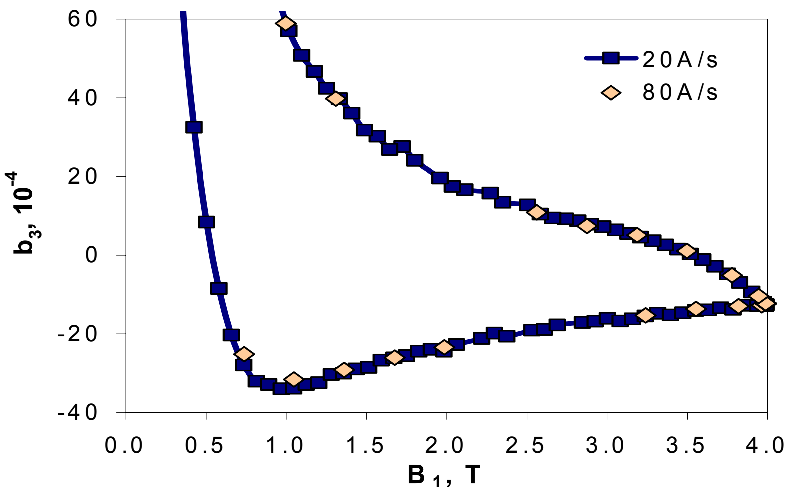
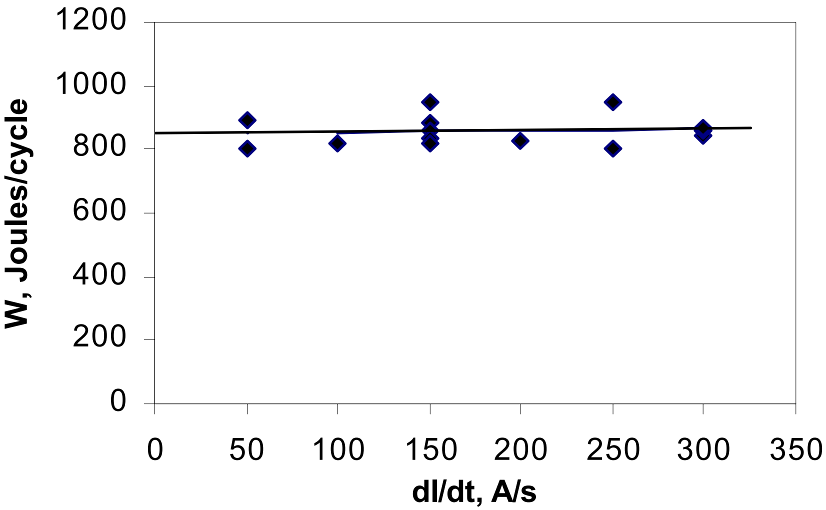
Eddy current effects





✓Nb_3Sn magnets fabricated using wind-and-react technique show large eddy current effects (Rc is small).

✓To increase Rc cable has a 25 μm SS core (first time tested in magnet).

✓Eddy current effect in b3 and b5 is small due to high Rc.

✓It is consistent with AC loss measurements.

✓Noticeable eddy current effect in B/I related to the large eddy currents in the Al spacers.

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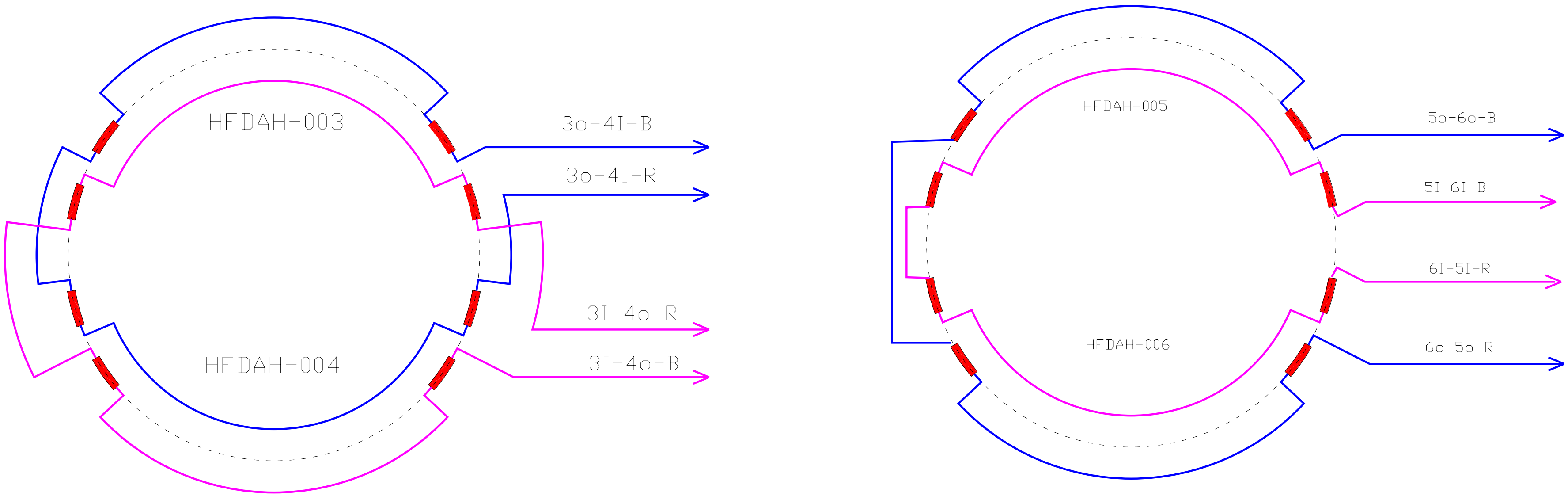
Quench heaters



Note:
5I-6I and 6I-5I repesent the heaters close to the parting plane
5o-6o and 60-5o represent the heaters close to the pole

Quench heater: four 0.025 mm thick and 12 mm wide SS strips connected in series and placed one in each quadrant.

Quench heater study

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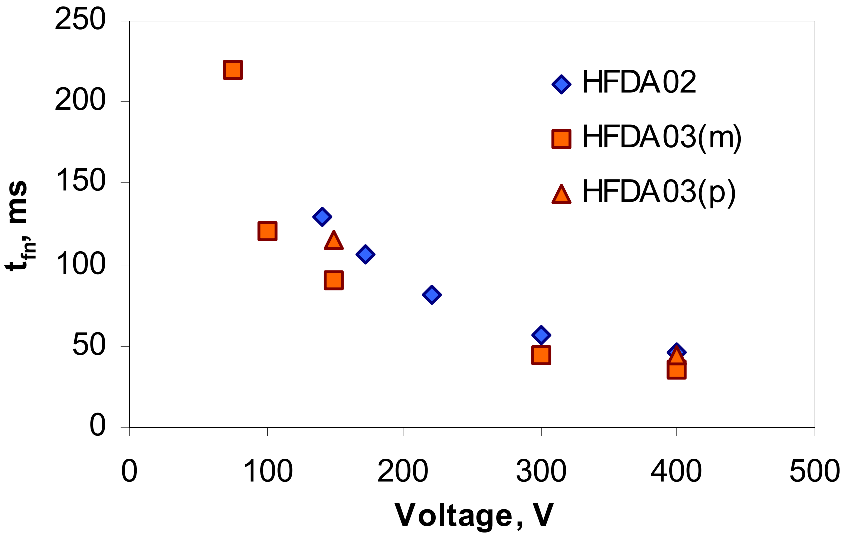

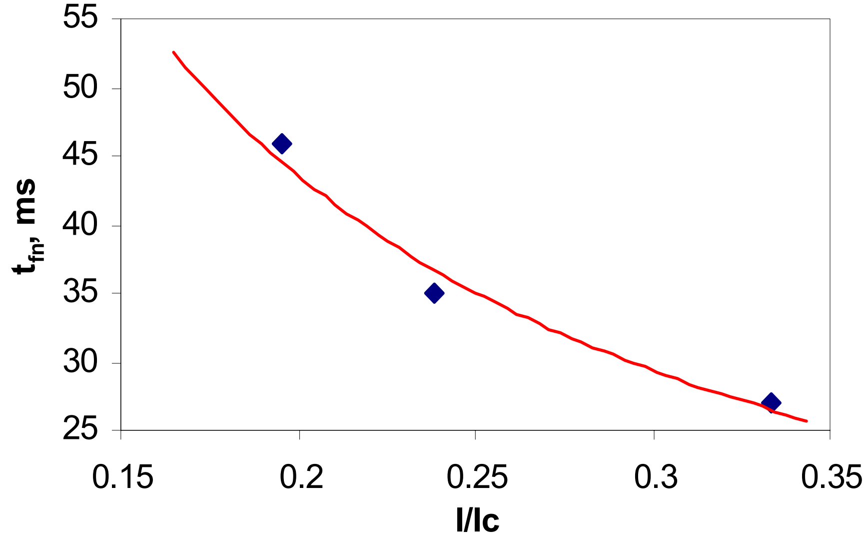

✓Even at low currents the measured t_{fn} is small.

✓Extrapolation to the currents corresponding to B~10-11 T and 10% Ic margin shows that heater efficiency in Nb_3Sn magnets is rather high (t_{fn}~20 ms) as in the NbTi accelerator magnets.

Summary

- 3 Nb_3Sn dipole short models were fabricated and 2 were tested.
- The low maximum quench current reached in both tested models was restricted by the quenches in the lead splices. The possible causes of that have been investigated including mechanical damages or degradation of Nb_3Sn coil leads during magnet fabrication, necessary changes were implemented.
- Quench heaters tested in both models demonstrated a high efficiency comparable with the heater efficiency in NbTi accelerator magnets.
- Field quality measurements of Nb_3Sn dipole models are consistent with the expectations.
- Large low-order geometrical harmonics are explained by the deviation of coil geometry from the nominal. Necessary improvements will be achieved with modified coil fabrication tooling and procedures, and part quality.

Summary

- The relatively large measured magnetization harmonics are consistent with the calculations based on the measured properties of Nb_3Sn strand used in these models.
- A passive corrector to minimize this effect was successfully tested and proved sound. Next two will be tested soon.
- The noticeable sextupole decay and "snapback" effect observed in NbTi accelerator magnets at injection has not been found in tested Nb_3Sn dipole models. This is not yet understood and will be studied further in future models.
- A stainless steel core in the cable has eliminated large eddy current effects seen in other Nb_3Sn magnets.
- Further fabrication and tests of models in this design series will be continued in order to achieve the design fields and field quality and study the reproducibility of magnet parameters.

Future Plans for SC Magnet Program

Outlines:

Program goals

Program status and issues

Program plans

Schedule and milestones

Resource projection

A. Zlobin

HFM Program goals

- Development of SC accelerator magnets operating at 4.3-4.5 with nominal magnetic fields above 10 T and large critical temperature margin for different applications
- Development and study of new SC strands, cables and structural materials
- Development of new cost effective and robust fabrication technologies
- Development of necessary expertise and infrastructure at Fermilab

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HFM program directions

1. VLHC magnets
   - Conceptual design studies
   - Model magnet R&D
2. LHC high-luminosity IR upgrade
   - Conceptual design studies
3. Magnets for Tevatron
   - Conceptual design studies
4. Magnet components
   - Strands and cables
   - Structural materials and components
   - Instrumentation

VLHC magnet development summary

- Conceptual design study:
  - Several designs of 10 T arc dipole magnets with vertical and horizontal bores
  - 400 T/m arc quads with both FF and FD configurations and vertical and horizontal bores
  - Arc D, Q and S correctors
  - Magnet cryostats and spool-pieces
- Several innovative and promising designs were developed
  - Single-layer common coil with low or high current and cold iron yoke
  - Warm yoke design with shell-type coils and horizontal bore arrangement
- Issues to be studied: IR D, Q and corrector designs, radiation-induced heat load, magnet thermal stability, etc.

VLHC magnet development summary

❖ Short model R&D:

- Two-layer cos-theta models based on the W&R technique
  - Two mechanical models were fabricated and tested
  - HFDA01, HFDA02 and HFDA03 were fabricated and tested
  - HFDA04 is being fabricated, test in May 2002
  - HFDA05 fabrication will start in May 2002

- Single-layer common coil models
  - Two mechanical models were fabricated and tested
  - HFDB01 and HFDB02 (R&W racetracks) were fabricated and tested
  - HFDC01 based on R&W technique is being fabricated
  - HFDC02 based on R&W or W&R approach is being optimized

- Issues: magnet fabrication technology, mechanics, <u>quench performance</u>, field quality, reproducibility

LHC IR upgrade

- Conceptual design studies:
  - LHC IR optics upgrade studies with 70-mm and 90-mm quads
  - Conceptual design of 90-mm Nb3Sn quadrupole
  - 70-mm quadrupole in HGQ collar
  - Issues:
    - establishing magnet target parameters (in collaboration with AP group and CERN)
    - development and comparison of different design and technological approaches for IR quadrupoles, correctors and separation dipoles
    - selection of conceptual magnet designs and basic technologies (end of FY2004)

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US LHC Accelerator Research Program

- Why do we need to participate in LHC ARP program?
  - It is generic since it addresses the most important issues related to the IR designs for high luminosity machines
  - It is practical since it is related to a real machine
  - It extends Fermilab's expertise in IR quadrupoles designing, fabrication and testing
  - It is an opportunity to develop new Nb3Sn accelerator magnet technology and use it in a real machine
  - It stimulates industry in development of new materials, and Nb3Sn strands and cables for HEP

SC Magnets for Tevatron

We are prepared to:

- Repair or replace any Tevatron magnets
- Modify or replace Tevatron spools
- Assemble and/or build additional Low Beta Quadrupoles (LBQ)
- Build new Tevatron IR quadrupoles based on LHC HGQ (for example, for a new BTeV IR)
- Develop any magnet needed for Fermilab accelerator complex

Material and component R&D

- Main mission: to provide support for the Fermilab and national SC magnet R&D programs
- Material R&D:
  - magnet structural materials
  - SC strands and cables
- Components:
  - passive correctors
  - quench protection heaters
  - instrumentation
- Several innovative and promising components and technologies were developed:
  - HT ceramic insulation and binder
  - effective end part design and technologies
  - correctors based on iron strips

HFM Program plans and directions

- Program principles:
  - Goal oriented magnet program
  - Magnet program goals are consistent with the 2002 HEPAP subpanel recommendations
  - Preliminary technical requirements are consistent with the goals
  - Schedule is coordinated with HEPAP timelines for Selected Roadmap Projects
  - Budget is realistic and consistent with the expected available funds
  - We coordinate and collaborate with other DOE National Labs
- HFM Program directions:
  - Continuation of VLHC HFM R&D
  - Start of 2nd generation LHC IR magnet R&D (with other Labs)
  - Material and component R&D

VLHC magnet R&D

- Short model R&D (FY2002-FY2009):
  - cos-theta dipole models based on the W&R approach (FY2002-FY2005)
    - Single-bore models
    - 2-in-1 models with warm iron yoke
  - Single-layer common coil dipole models based on the R&W or W&R approach (FY2002-FY2009)
  - Issues to be studied: design, technology, materials, performance, reproducibility, long-term performance
- Long dipole prototypes (FY2009-FY2011)
  - Issues to be resolved: long magnet technology and performance, magnet cost

Outcome of the VLHC magnet R&D

The outcome of the VLHC magnet R&D will be:

- the conceptual design and technology of Nb3Sn arc dipole magnets suitable for the VLHC high field stage
  - Cos-theta or common coil design concept
  - W&R or R&W technique
- magnet and component specifications necessary for the VLHC design development
- VLHC arc magnet cost justification

2nd generation LHC IR magnet R&D

- Short model R&D (FY2003-FY2009):
  - 70-mm Nb3Sn quadrupole models with MQXB mechanical structure (FY2003-FY2006)
  - depending on the results of magnet conceptual design study and IR upgrade scenario either 90-mm (or larger bore or higher gradient) Nb3Sn quadrupole models or double bore IRQ (FY2005-FY2009)
  - Issues to be studied: design, technology, materials, performance, reproducibility, long-term performance

- Full-scale IRQ prototypes (FY2009-FY2011)
  - Issues to be resolved: long magnet technology and performance, magnet cost

Outcome of the LHC IR magnet R&D

- The outcome of the LHC IR magnet R&D for the US LHC collaboration:
  - magnet and component specifications needed for the detailed design of LHC IR
  - the design and technology of Nb3Sn quadrupole magnets suitable for the LHC high-luminosity IR upgrade
  - the cold-mass full-scale prototype and tooling
  - the cost and the schedule for the LHC IR upgrade

- The outcome for the VLHC program:
  - the conceptual design and the cost of the VLHC interaction regions can be justified
  - strong international collaboration of accelerator physicists and magnet developers will exist

SC Magnets
at Fermilab

HFM Program schedule and milestones

	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11
VLHC Dipoles										
Cos-theta	2	2	2	1						
Com.coil	1	1	2	2	3	3	3	3		
Long prototype								Des., tool.	1	1
Nb3Sn IRQ										
Design Study										
70-mm		Des., tool.	1	2	1					
90-mm				Des., tool.	1	2	4	4		
Prototype								Des., tool.	1	1
Components										

The number of models is consistent with the program goals

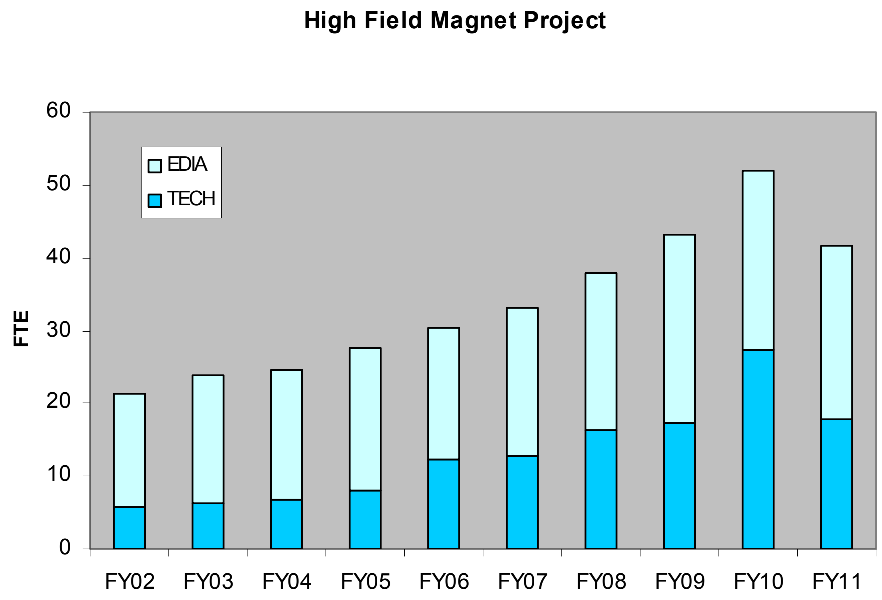
HFM milestones:

- FY04 – IRQ design choice
- FY08 – IRQ and VLHC dipole prototype choice
- FY11 – VLHC HFM conceptual design and technology choice
- FY11 – LHC IR upgrade design, schedule and cost estimate

LFM milestone:

- if a staged approach to VLHC which involves LF magnets is taken then Superferric or alternative low field magnet development program will restart in time

HFM Program Man-power Projection



		FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11
IRQ	Tech	0	0.4	0.4	1.6	6	6	10	11	13	8
	EDIA	0	1.6	1.6	8	8	10	12	12	11	11
HFD	Tech	5	5	5	5	5	5	5	5	13	8
	EDIA	14	14	14	10	8	8	8	12	11	11
SC&Cable	Tech	0.8	0.8	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2
	EDIA	1.5	2	2	2	2	2.0	2.0	2	2.0	2
HFM	Tech	6	6	7	8	12	13	16	17	27	18
	EDIA	16	18	18	20	18	20	22	26	25	24
	total	21	24	25	28	30	33	38	43	52	42

LHC HGQ 1999 (R&D peak): EDIA=36, Tech=15

SC Magnets
at Fermilab

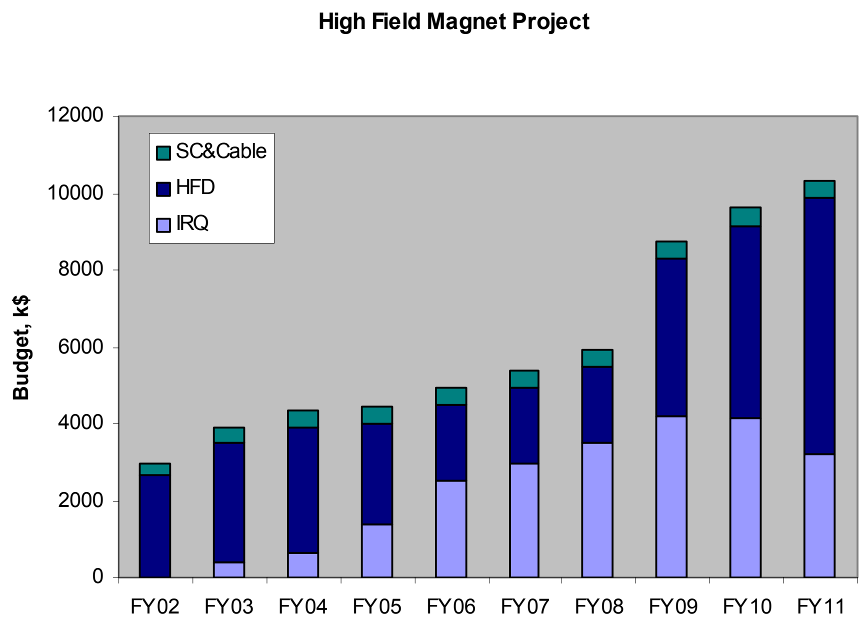
Staff issues

- We have strong SC magnet development and test team

- We will continue to train graduate and postgraduate students and post-docs in the field of accelerator magnet science and technology growing the next generation of magnet scientists and benefiting from their active participation in our program

- Staff issues:
  - Magnet scientist:
    - Functions: SC magnet development, tests and data analysis
    - Status: 3 scientists + 1 Ph.D. student
    - G. Sabbi – LBNL
    - P. Bauer – LC – not replaced
  - SC material engineer or engineering physicist:
    - Functions: SC strand and cable development and characterization
    - Status: 1 engineer + 1 student
    - J. Ozelis – JLab – not replaced

HFM Program Budget Projection



	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11
IRQ, k$	0	380	620	1405	2540	2978	3510	4199	4126	3194
HFD, k$	2650	3125	3295	2575	1965	1965	1965	4085	5025	6677
SC&Cable, k$	330	382	438	458	458	458	458	458	458	458
HFM, k$	2980	3887	4353	4438	4963	5401	5933	8742	9609	10328

Conclusions

- Fermilab has a strong magnet team capable of efficiently solving complex problems related to the SC accelerator magnet design and technology development, magnet fabrication and tests
- Fermilab has a unique infrastructure that allows extensive engineering, fabrication and testing of SC magnet short models and long prototypes, structural component and materials studies including SC strands and cables
- Fermilab has a strong and healthy HFM program which has already resulted in developing several innovative magnet designs and techniques, and obtaining unique experimental data related to magnet and component performance parameters
- Fermilab HFM R&D program will continue to be focused on the development of SC accelerator magnets for HEP following the directions and milestones outlined in the 2002 HEPAP Subpanel Report, in particular for
  - Tevatron needs
  - LHC high-luminosity IR upgrades
  - future Very Large Hadron Collider